[redacted]

Chapter 3

THERMAL RADIATION PHENOMENA [redacted]

[redacted] Within a few seconds after the explosion a typical low altitude nuclear fireball emits about a third of the weapon yield as infrared, visible, and ultraviolet radiation (see Figure 4-1). This sudden pulse of thermal energy may damage any target that is susceptible to high temperatures. The damage may take many forms, but the effects that are most frequently of concern are fires that start as the result of ignition of thin combustible materials (e.g., paper or dried leaves) and injuries to personnel, in the form of burns.

[redacted] The thermal pulse decays as the fireball fades, but there is no specific time that marks the end of the thermal radiation from the fireball. At late times, as the radioactive cloud rises, the heated air in the nuclear cloud still radiates some thermal energy; however, this radiant energy is released so slowly that it has little military importance. Therefore, in this chapter, the terms "thermal radiation phenomena," "thermal effects," and "thermal pulse" only pertain to that portion of the radiated energy that could be termed the "prompt thermal pulse."

[redacted] This restriction in the meanings of terms such as "thermal effects" excludes a number of nuclear burst phenomena that are thermal in the broader sense. For example, fireball rise is a thermal effect; the fireball is buoyant for the same reason that a hot-air balloon is buoyant. Another effect that properly could be termed thermal is the radiation of X-ray energy by the nuclear source. The X-ray energy is the thermal radiation that is characteristic of an extremely high temperature source (see Chapter 4). In many situations, e.g., low altitude bursts, this radiation has no direct effect on targets, because it is absorbed by air close to the source. In other situations, notably aerospace vehicles exposed to high altitude detonations, this X-ray energy becomes one of the most important direct damage mechanisms. This damage mechanism is discussed in Section V, Chapter 9.

[redacted] RADIANT EXPOSURE [redacted]

[redacted] Four variables determine the effects of the thermal pulse on a target:

- The amount of energy that is incident on the target.
- The time history of the thermal pulse.
- The spectral distribution of the radiant energy.
- The directional characteristics of the incident radiation, e.g., does it come directly from the source, or is it scattered and therefore arrives from many directions.

In most cases of military interest the first of the variables is dominant. A careful analysis cannot ignore the other three, but a *preliminary* evaluation of a thermal environment, for example, a calculation to determine whether a thermal problem exists, often can be based on the total energy received.

[redacted] The energy delivered by the thermal pulse usually is specified in terms of *radiant exposure*, the energy per unit area incident on the target surface. It is denoted by the symbol Q and is conventionally measured in units of calories per square centimeter (cal/cm^2). The factors that affect the radiant exposure are discussed separately in the following paragraphs.

[redacted]

[redacted]

3-1 Thermal Partition [redacted]

[redacted] The ratio of the thermal energy radiated by the fireball of a nuclear explosion to the total yield is *thermal partition* (sometimes called *thermal efficiency*), denoted by the symbol f. For burst altitudes below 100,000 feet and yields between 1 kt and 10 Mt, values of thermal partition may be determined from Figure 3-1. For higher burst altitudes, thermal partition must be determined by the method described in paragraph 3-19. If the burst is below $180W^{0.4}$ feet (where W is the yield in kilotons), it is classed as a surface burst and the thermal partition should be determined by the method described in paragraph 3-9.

[redacted]

[redacted]

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Accession For	
NTIS GRA&I	☒
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A-1	

QUALITY INSPECTED 4

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[redacted] [redacted]

[redacted]

Problem 3-1. Calculation of Thermal Partition

[redacted] Figure 3-1 contains a family of curves that show the thermal partition as a function of yield and height of burst. The data in Figure 3-1 apply to yields between 1 kt and 10 Mt and to burst altitudes from $180W^{0.4}$ feet (where W is the yield in kt) to 100,000 feet.

[redacted] *Example* [redacted]

Given: A 10 Mt explosion at an altitude of 39,000 feet.

Find: The thermal energy that is radiated.

Solution: From Figure 3-1, the thermal partition is [redacted]

Answer: The thermal energy radiated is

[redacted]

[redacted] *Reliability* [redacted]:

[redacted] The shapes of the contour lines in Figure 3-1, and the precision with which values may be read from these lines suggest clearly established relations between yield, altitude, and thermal partition; however, the contour lines were obtained by fitting curves to the results of computer code calculations. Although many aspects of the computed results have been compared to experimental data, and the comparisons were favorable, the thermal partitions that the code predicts have not been confirmed definitely. [redacted]

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[redacted] Data for higher altitudes and higher yields are discussed in paragraph 3-19; data for surface bursts are described in paragraph 3-9, and data for special types of weapons are described in paragraph 3-17.

[redacted] *Related Material:* See paragraph 3-1. See also paragraphs 3-9 and 3-19.

Page 3-4 deleted.

[redacted]

3-2 Range Effects [redacted]

[redacted] As the thermal energy propagates away from the fireball, the divergence that results from the increasing area through which it passes causes the radiant exposure to decrease as the inverse square of the slant range. At a slant range R centimeters from the source, the thermal energy is distributed over a spherical area of $4\pi R^2$. Since the thermal yield in calories is 10^{12} Wf*, where W is the yield in kilotons, the radiant exposure at a distance R cm in a clear atmosphere is

$$Q = \frac{10^{12} Wf}{4\pi R^2} \text{ cal/cm}^2.$$

[redacted] Kilofeet and kilometers are more convenient units than centimeters for measuring the range from a nuclear burst. Appropriate conversion factors change the form of the equation to

$$Q = \frac{100 \ Wf}{4\pi R_{km}^2} = 7.96 \ Wf/R_{km}^2 \ \text{cal/cm}^2,$$

and

$$Q = 85.7 \ Wf/R_{kft}^2 \ \text{cal/cm}^2,$$

where R_{km} and R_{kft} are slant ranges in kilometers and kilofeet, respectively.

[redacted] TRANSMITTANCE [redacted]

[redacted] The equations presented above ignored the attenuation by the atmosphere that would affect the thermal energy received by a target. In many cases, particularly when the air is clear and the range is short, atmospheric attenuation is not important. In other situations, scattering and absorption of thermal energy by the atmosphere can reduce the amount of thermal energy reaching the target significantly.

[redacted] In addition to atmospheric attenuation, other effects also must be considered. A cloud layer above a fireball can scatter radiation downward and can increase the thermal energy that reaches the ground. If the ground also is highly reflecting, e.g., if the ground is covered by a layer of snow, further enhancement of the thermal radiation may result.

[redacted] All of these effects are approximated by one factor, the transmittance T. Transmittance is the ratio of the radiant exposure at a target facing the fireball to the radiant exposure that the target would receive if the intervening atmosphere were perfectly transparent.

[redacted] Adding the transmittance factor to the equations given in paragraph 3-2 gives

$$Q = \frac{7.96 \ WfT}{R_{km}^2} \text{ cal/cm}^2,$$

and

$$Q = \frac{85.7 \ WfT}{R_{kft}^2} \text{ cal/cm}^2.$$

The corresponding expressions for slant range in terms of yield and transmittance are†

$$R_{km} = 2.82 \sqrt{WfT/Q}$$

$$R_{kft} = 9.26 \sqrt{WfT/Q}$$

3-3 Specification of Transmittance [redacted]

[redacted] A difficult task in applying transmittance data to a thermal problem is deciding which model atmosphere to use. Various model

*[redacted] One kiloton equals 10^{12} calories (see Table 1-2).

†[redacted] A relationship that is easy to remember and that is reasonably correct if it is assumed that the thermal partition, f = 1/3, and the transmittance, T = 1.0, is that the radiant exposure at one statute mile is about Q = 1 cal/cm^2 per kt.

[redacted] atmospheres are identified in terms of parameters that can be measured without special instruments. The first of these is visual range, a parameter that indicates the light transmission properties of the layer of air near the surface. A second is the appearance of the sky, which can be used to indicate the amount of haze or fog that thermal radiation from a high altitude burst must penetrate to reach a target at the surface.

[redacted] Although transmittance can be calculated between any two points in space, a large number of thermal problems involve ground targets. The material presented in this paragraph has been developed primarily to calculate transmittance between the point of burst and a target on the ground. These methods may be extended to calculate transmittance to airborne targets, but the validity of such calculations has not been checked as carefully as has the validity of transmittance calculations for ground targets.

[redacted] Whether or not a particular transmittance calculation is useful depends on the nature of the problem. If the burst is a specific test, the weather at the particular time can be determined, and appropriate transmittances can be assigned. If the burst involves a hypothetical attack at some unknown date, a reliable prediction of the transmittance, and, as a result, the extent of the thermal damage from a particular explosion, is impossible. The atmosphere could be clear or foggy; light combustibles such as leaves or paper could be wet or dry. Yield and position of the weapon are unknown and can only be estimated.

[redacted] Two types of problems provide answers that are sufficiently reliable to be useful. A calculation intended to be conservative from the point of view of the defense indicates the level of damage that an explosion could inflict on a day when the air is clear and the ground is dry. This type of calculation is useful for designating safe areas or designing defense systems. Useful answers also can be obtained in tactical situations. The minimum intercept altitude of a defensive missile might be lowered on a foggy day, and an attacking force might use current weather conditions to determine whether their weapon would produce significant thermal damage or whether they must rely primarily on other effects.

3-4 Model Atmospheres [redacted]

[redacted] The typical cloudless atmosphere has a haze layer near the surface. Often this haze layer is relatively uniform, with a sharply defined upper boundary; when cumulus clouds are present, the bases of these clouds may mark the top of the haze layer.

[redacted] At higher altitudes, the air usually is clearer, and, in the absence of clouds, about 80 percent of the attenuation of radiation from a high altitude source occurs at altitudes below 3 miles. The low density air several miles above the surface offers almost no interference to radiation in the visible and infrared regions of the spectrum.

[redacted] A set of cloudless model atmospheres provides an approximate representation of the optical properties of real atmospheres. These models only represent the atmosphere in a general way, but they form a basis for transmittance calculations. They have the advantage that selection of the appropriate model is based on the simple criterion of daytime visual range. The model atmospheres are cloudless; correction factors introduced into the transmittance calculations account for the effects of clouds. These model atmospheres and the empirical equations that are used with them give reasonably accurate estimates of transmittance if the transmittance is above about 0.1.

[redacted] Current reports consistently use visibility, which is called "visual range" in this chapter, as one means for classifying model atmospheres; however, no standard definition of visibility is adopted consistently. The atmo-

[redacted] sphere described in this chapter as having a visual range of 16 miles would be assigned a visibility of 12 miles by at least one author and a visibility of 24 miles by some others.

[redacted] The extent to which the atmosphere impedes the flow of thermal energy and limits visibility depends largely on the amount of scattering of radiant energy by atmospheric particles. Absorption of energy also affects radiative transport, but absorption usually is less important than scattering. A description of these phenomena is the first step in explaining visual range and transmittance.

[redacted] The thermal radiation of concern in this chapter consists of electromagnetic radiations from the ultraviolet to the infrared. The photons that make up electromagnetic radiations can react with matter in many complex ways, but the photons that constitute the thermal radiation spectrum of a nuclear fireball interact almost exclusively by being absorbed or elastically scattered. If the photon is absorbed, it gives up its energy to the absorbing particle, and this energy ultimately appears as heat. Scattering may be thought of as reflection from a small particle. Its effect is to change the direction in which the photon is traveling. The term "elastic" means that the photon does not lose energy during the scattering process. Other interactions of electromagnetic radiations with matter that are more probable for higher frequency (shorter wavelength) radiations than those of the thermal radiation are described in paragraph 4-3, Chapter 4.

[redacted] The scattering and absorption properties of the atmosphere depend partly on the wavelength of the radiant energy. Wavelength is often measured in microns (1 micron = 10^{-6} meter), for which the symbol is μ. Wavelengths in the visible spectrum may be identified by the relation between wavelength and color: light with a wavelength of 0.7 μ is red; 0.58 μ light is yellow; and 0.48 μ light is blue. White light is a mixture containing all wavelengths in the visible spectrum, which extends from 0.38 to 0.78 μ. The infrared spectrum consists of radiant energy at wavelengths longer than 0.78 μ, and the ultraviolet spectrum consists of radiant energy at wavelengths shorter than 0.38 μ.

[redacted] The energy transport properties of atmospheric particles may be expressed in terms of scattering and absorption cross sections, which are fictitious areas that are a measure of the probability that scattering or absorption will occur. Particles that are small compared to the wavelength of light have scattering cross sections that are inversely proportional to the fourth power of the wavelength. Therefore, air molecules scatter light from the extreme blue end of the visible spectrum (wavelength = 0.38 μ) about 16 times as effectively as they scatter light from the red end of the spectrum (wavelength = 0.78 μ). Blue smoke, which consists of very small particles, has similar scattering properties. Particles that are large compared to the wavelength of light (e.g., haze or fog particles) have scattering cross sections that are much less dependent on wavelength. Individual particles have a scattering cross section that varies somewhat with wavelength, but the mixture of particle sizes found in a haze or fog usually results in an average cross section that is nearly independent of wavelength.

[redacted] The sky is blue because most of the scattering at high altitudes is by air molecules, which scatter blue light more efficiently than they scatter other colors of the visible spectrum. A distant mountain appears blue on a clear day for the same reason.

[redacted] The scattering properties of larger airborne particles may be observed on days when a very light haze reduces visibility to about 10 miles or less. Near the surface, scattering by haze particles contributes more to the light in the air than does scattering by air molecules. The sky still appears blue, but the color is not as deep as [redacted] it would be on a clearer day. Distant hills and the sky near the horizon appear to be more gray than blue, which indicates that the lower atmosphere is scattering all wavelengths of light about equally.

[redacted] Water droplets cause nearly all of the scattering that occurs in a fog or a thick cloud. Consequently, clouds are white and fogs tend to wash out all impressions of color.

[redacted] Absorption usually has little effect on visible light, but it can affect the infrared and ultraviolet portions of the spectrum significantly. The principal absorber of thermal energy usually is water vapor, which has strong absorption bands in the infrared spectrum. Dry air transmits infrared energy more efficiently than humid air. Carbon dioxide and other gases present in the atmosphere in small amounts also absorb infrared energy.

[redacted] Ultraviolet energy is absorbed most strongly at the shorter wavelengths: the limiting wavelength that air in the lower atmosphere will transmit is about 0.2 micron. Ozone, appreciable quantities of which are found between roughly 60,000 and 80,000 feet, absorbs ultraviolet radiation with wavelengths shorter than 0.29 micron. As a result of these absorption bands ultraviolet energy that reaches the earth from the sun is almost entirely limited to the spectral band between 0.38 micron (the violet edge of the visible spectrum) and 0.29 micron.

[redacted] Dark colored particles absorb appreciable energy in all regions of the thermal spectrum. Dust, smoke, and the smoky haze from large cities fall into this category.

[redacted] Detailed calculations of the complex scattering and absorption processes that can occur between a nuclear explosion and a target require computer codes that are capable of considering detailed changes in the atmosphere and the effect that these changes can have on the entire spectrum of frequencies emitted by the fireball. Monte Carlo calculations have been performed for several model atmospheres and for several discrete wavelengths; however, as of this time, these calculations have not been generalized into a form that is suitable for inclusion in this manual. Therefore, the formulas and curves for atmospheric transmittance that are given below are based on a simplified model based on the concept of effective optical height for single wavelengths.

[redacted] One way to specify the attenuating properties of the atmosphere as a function of altitude is to assume that the transmittance between the point of burst and ground zero follows an equation of the form

$$T = e^{-\tau(h)},$$

where T is transmittance and $\tau(h)$ is the *effective optical height* of the burst height h. This concept was applied in 1966 to specify one particular model atmosphere for which the visual range is 16 miles.* The attenuation for light of 0.65 micron wavelength was used to specify $\tau(h)$. This choice was a purely empirical one, used because it brought the calculated values of transmittance into general agreement with experimentally determined values. The wavelength that was selected is attenuated less than is the thermal radiation spectrum as a whole;

*[redacted] "Transmissivity of the Atmosphere for Thermal Radiation from Nuclear Weapons" (see bibliography). A 12 mile visual range was assigned to this model atmosphere. This choice was based on a comparison between a large number of visual range estimates at an airport weather station and simultaneous measurements with instruments designed to measure meteorological range. The 16 mile figure is used here because it is consistent with the definition of visual range given in this chapter. Qualitatively, this range is defined as the distance at which a dark object silhouetted against the sky is visible and recognizable. This range is more specifically defined in paragraph 3-7.

[redacted] Although the specification for this model atmosphere has been changed, the reason for having assigned the 12 mile figure carries a useful warning. There is no assurance that even trained meteorologists will make estimates that are consistent with a precise mathematical definition of visual range.

[redacted] therefore, this choice makes allowance for additional energy that reaches the target by scattering. For bursts below one-quarter mile and surface targets, a wavelength of 0.55 microns was used together with a buildup factor, as described below.

[redacted] Figure 3-2 shows $\tau(h)$ as a function of altitude for this particular model atmosphere. This model shows no attempt to represent an abrupt increase in transparency at the top of the haze layer; optical height is a smoothly varying function of altitude. This approximation to the actual atmosphere does not appear to introduce serious error into the calculations, and it is more convenient than a model atmosphere that requires an estimate of the height of the haze layer as well as an estimate of visual range.

[redacted] When visual range is different from 16 miles, the model atmosphere is specified by multiplying the values of effective optical height in Figure 3-2 by $16/V$, where V is visual range in miles. For example, if the visibility is 8 miles, all values of optical height are doubled, indicating that transparency at all altitudes is reduced by a factor of 2. This transformation may be stated mathematically as

$$\tau(h)_V = \tau(h)_{16} \frac{16}{V}$$

where $\tau(h)_V$ is the effective optical height at a given altitude for the model atmosphere for which visual range is V and $\tau(h)_{16}$ is the effective optical height of the 16 mile model atmosphere at the same altitude.

[redacted] Visual range, a surface measurement, is a poor criterion for predicting the clarity of the air a few miles up. Although there is some correlation between these two quantities, the main justification for this somewhat arbitrary procedure is that the optical thickness assigned to the upper atmosphere, since it is a small fraction of the total optical thickness, has little influence on the calculated transmittance to targets on the ground.

[redacted] If the burst height is less than about one-quarter mile, the line-of-sight path from the burst to the target passes through air which, in most cases, has optical properties that are fairly uniform. In a uniform atmosphere, the attenuation of a direct beam of thermal energy may be related to the visibility of distant objects by the equation.

$$T_d = e^{-2.9 \ R/V},$$

where T_d is the transmission coefficient for *direct* flux over a path of slant range R, and V is visual range. As mentioned above, scattered as well as direct flux must be considered. Consequently, transmittance is larger than the transmission coefficient for direct flux and is given approximately by the following empirical equation:

$$T = e^{-2.9 \ R/V} \ (1 + 1.9 \ R/V).$$

[redacted] The exponential factor in this equation accounts for energy loss from the direct beam by scattering. The expression in brackets is a buildup factor that accounts for energy scattered toward the target. This equation does not specifically involve any property of the model atmosphere other than visual range; however, the properties of the model atmosphere are involved implicitly, because the rate at which transparency changes with altitude helps determine the magnitude of the coefficient 1.9 in the buildup factor. Figure 3-3 shows this relation in graphical form.

[redacted] When the burst height h is greater than about one-quarter mile, transmittance may be calculated from

$$T = e^{-\tau(h) \ \frac{16}{V} \frac{R}{h}}$$

[redacted]

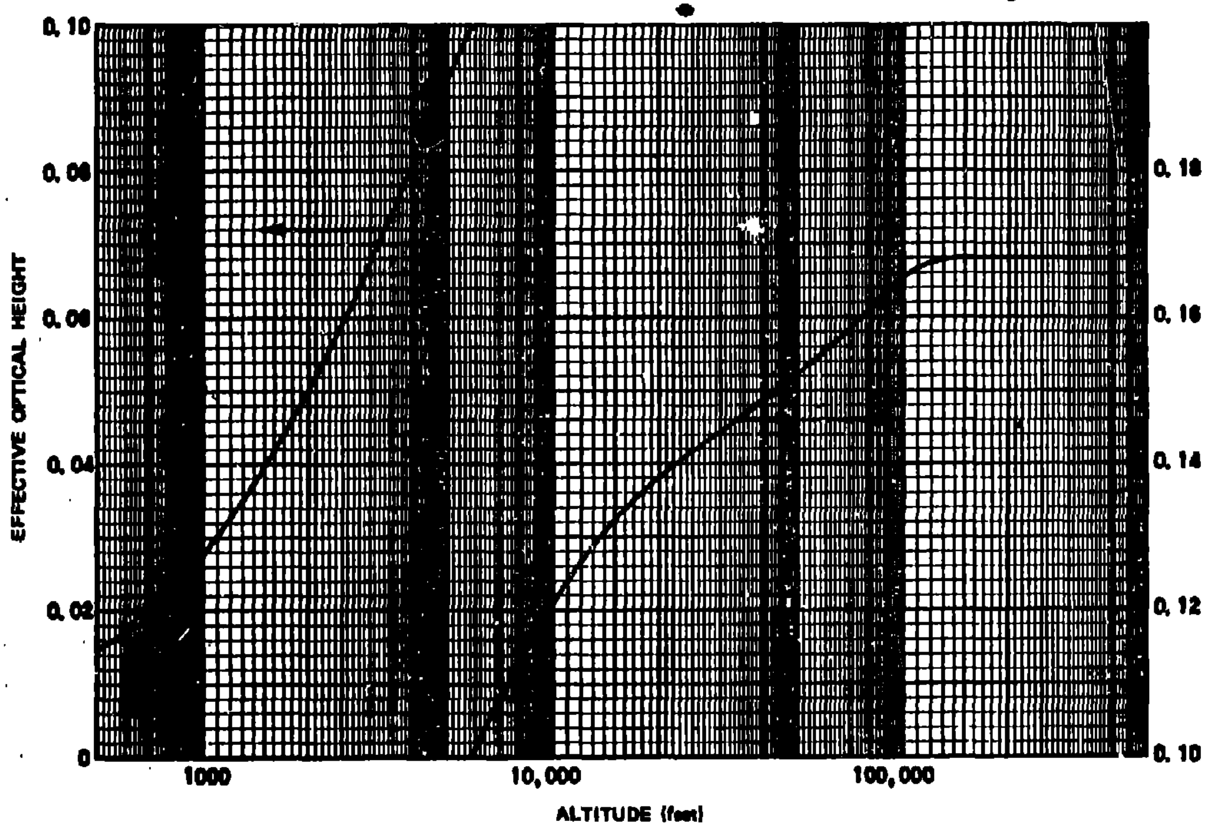

Figure 3-2. [redacted] Effective Height of Model Atmosphere (Visual Range = 18 Miles) [redacted]

[redacted]

[redacted]

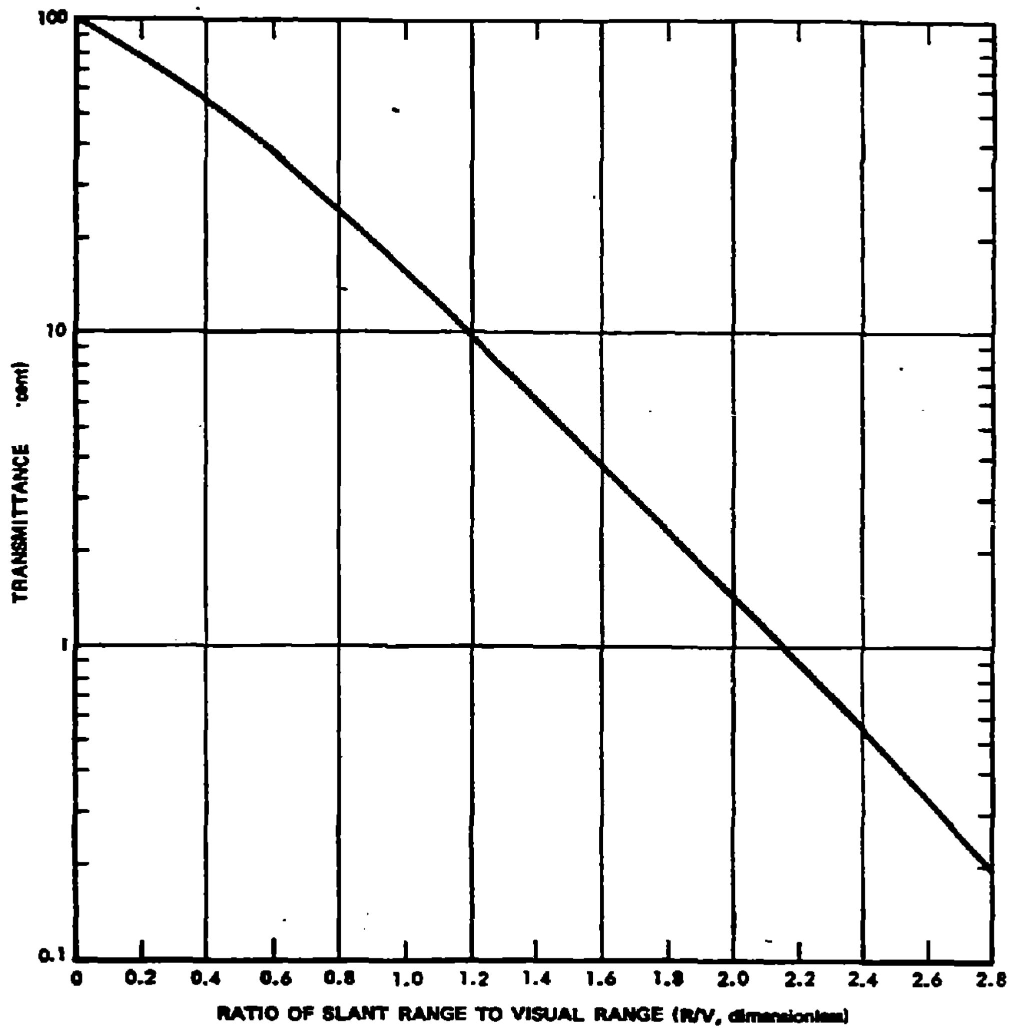

Figure 3-3. [redacted] Transmittance Between a Burst
Within 1/4 Mile of the Surface
and a Target on the Ground [redacted]

[redacted]

[redacted] where $\tau(h)$ (from Figure 3-2) is the effective optical height of the model atmosphere with 16 mile visual range, and $\tau(h)$ $16/V$ is the effective optical height in the model atmosphere for which visual range is V. The factor R/h converts effective optical height to the effective optical distance measured along the slant path of length R, where h is the height of burst.

[redacted] The two equations just given are for cloudless (but not necessarily clear) atmospheres. The effects of cloud layers are considered later in this subsection.

[redacted] Height-of-burst curves provide a convenient means for applying these transmittance equations to thermal effects calculations. Figures 3-4 through 3-14 are a series of such curves.

[redacted] The height-of-burst curves do not show transmittance data for bursts above 100,000 feet (with the exception of Figure 3-13a). Transmittance above this altitude depends only on elevation angle. If the burst is above 130 kilofeet, the transmittance is independent of altitude, and the contours become straight lines. This is illustrated for a 16 mile visual range in Figure 3-13a, in which the height of burst is extended to 250,000 feet. As mentioned above, these curves are based on two empirical equations, one of which applies when the burst height exceeds one-quarter mile (1.32 kilofeet) and the other of which applies to lower bursts. The discontinuities that occur where these two families of curves meet has no particular significance other than to suggest the degree of uncertainty inherent in any transmittance data. The discontinuities have been allowed to remain; joining the contour lines would produce shapes that may have no physical basis (for example, the curves should not be interpreted to imply that for short ground ranges the optimum burst height for thermal effects on the ground is necessarily below 1/4 mile).

Problem 3-2. Calculation of Radiant Exposure

[redacted] Figures 3-4 through 3-14 show atmospheric transmittance as a function of height of burst and ground distance for various visual ranges. These curves, together with the equations given in paragraph 3-2 allow the calculation of radiant exposure for a variety of circumstances.

[redacted] For bursts above one-fourth mile height of burst, interpolation between the figures (to obtain data for visual ranges other than those for which curves are provided) may be accomplished as follows:

$$T_2 = T_1^{\,V_1/V_2}$$

where T_1 is the label of a given contour line on a figure for a visual range of V_1 and T_2 is the label that this same curve would have if the figure were for a visual range of V_2. If the height of burst is below one-fourth mile, the transmittance may be obtained from Figure 3-3 for any combination of slant range and visual range.

[redacted] *Example 1* [redacted]:

Given: A 5 kt nuclear warhead is being considered for a defensive missile warhead.

Find: The minimum burst altitude such that the radiant exposure on the ground will not exceed 1 cal/cm^2.

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[redacted]

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[redacted]

[redacted] *Example 2* [redacted]

Given: A 100 kt explosion at an altitude of 10,000 feet at a location where the visual range is 16 miles.

Find: The thermal radiant energy incident on a target at a ground distance of 9,000 feet from ground zero.

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[redacted]

[redacted]

[redacted] *Reliability:* The calculated transmittances exceeding 0.1 are believed to be correct to ±30 percent; however, this tolerance is seldom required in practical problems. When transmittance exceeds 0.1, the product fT is believed to be within the range obtained by setting upper and lower limits on f as specified in "Reliability" in Problem 3-1. The reliability of transmittance calculations decreases as transmittance decreases. Transmittances below 0.1 are very uncertain, and errors that amount to a factor of 2 to 10 are not unusual. When correction factors for reflecting surfaces are required, an additional tolerance of ±30 percent should be applied to the fT product.

[redacted] *Related Material:* See paragraphs 3-2 through 3-6.

[redacted]

[redacted]

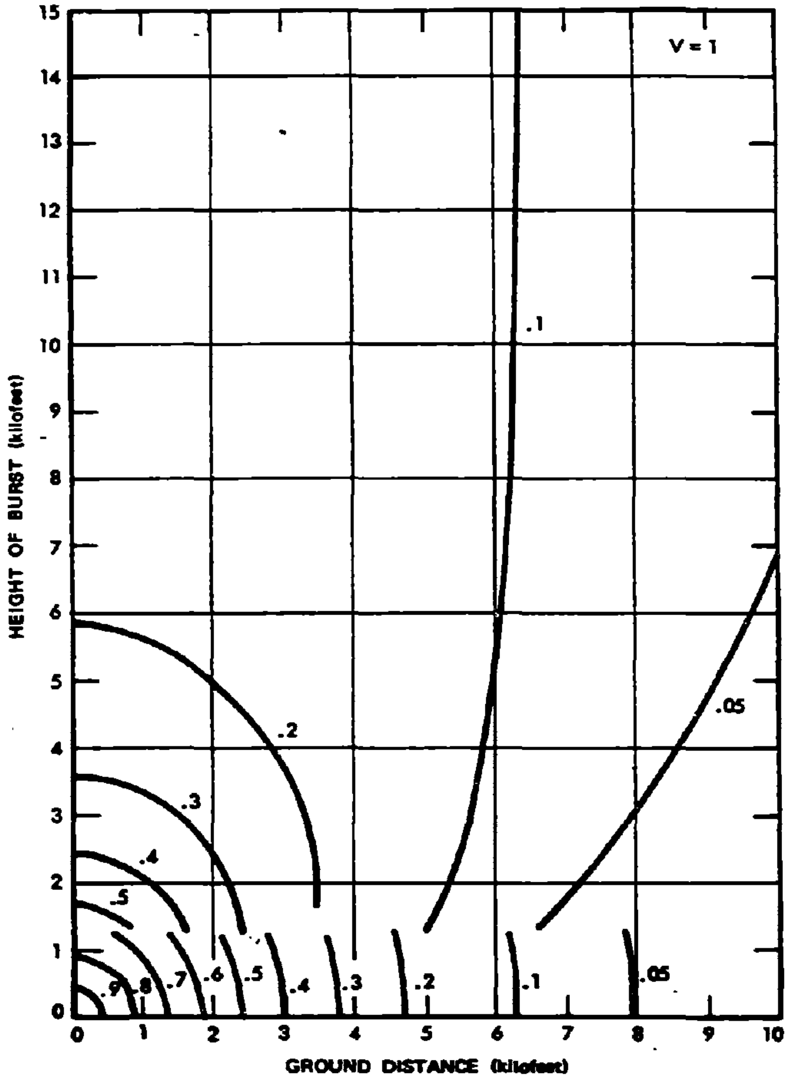

Figure 3-4. [redacted] Transmittance to a Target on the Ground on a Clear Day (Visual Range = 1 Mile) [redacted]

[redacted]

[redacted]

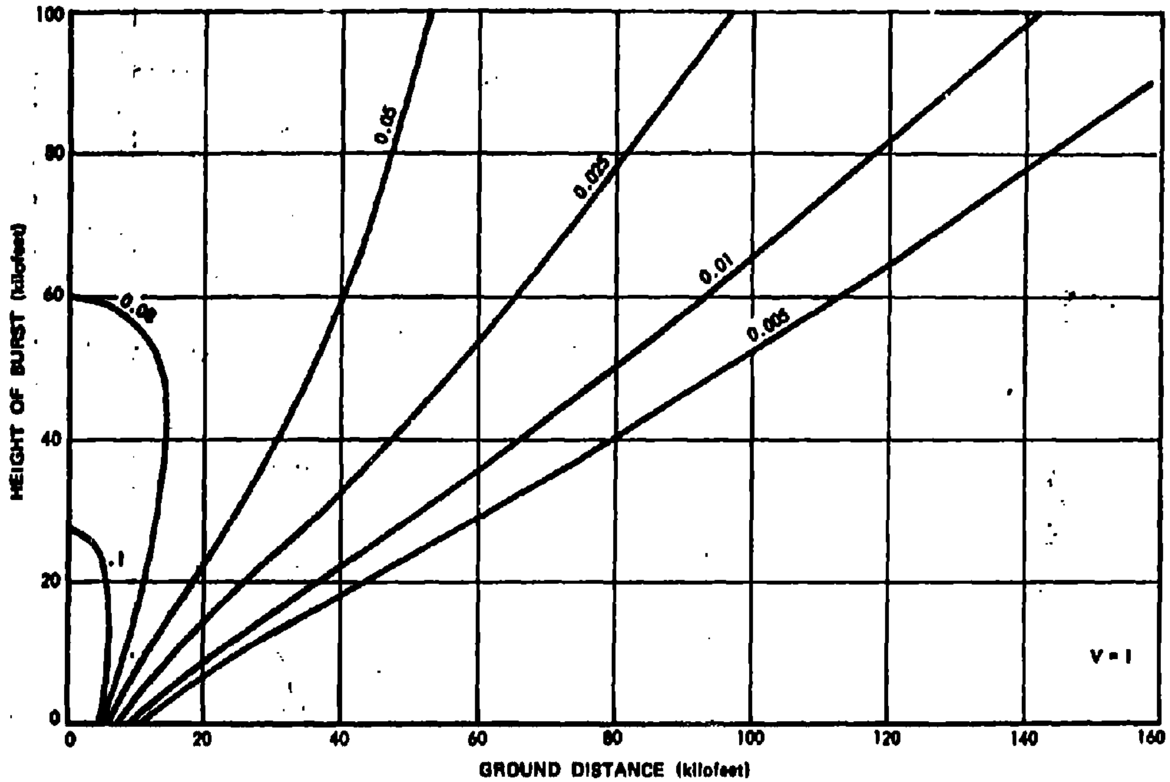

Figure 3-5. [redacted] Transmittance to a Target on the Ground on a Clear Day (Visual Range = 1 Mile) [redacted]

[redacted]

[redacted]

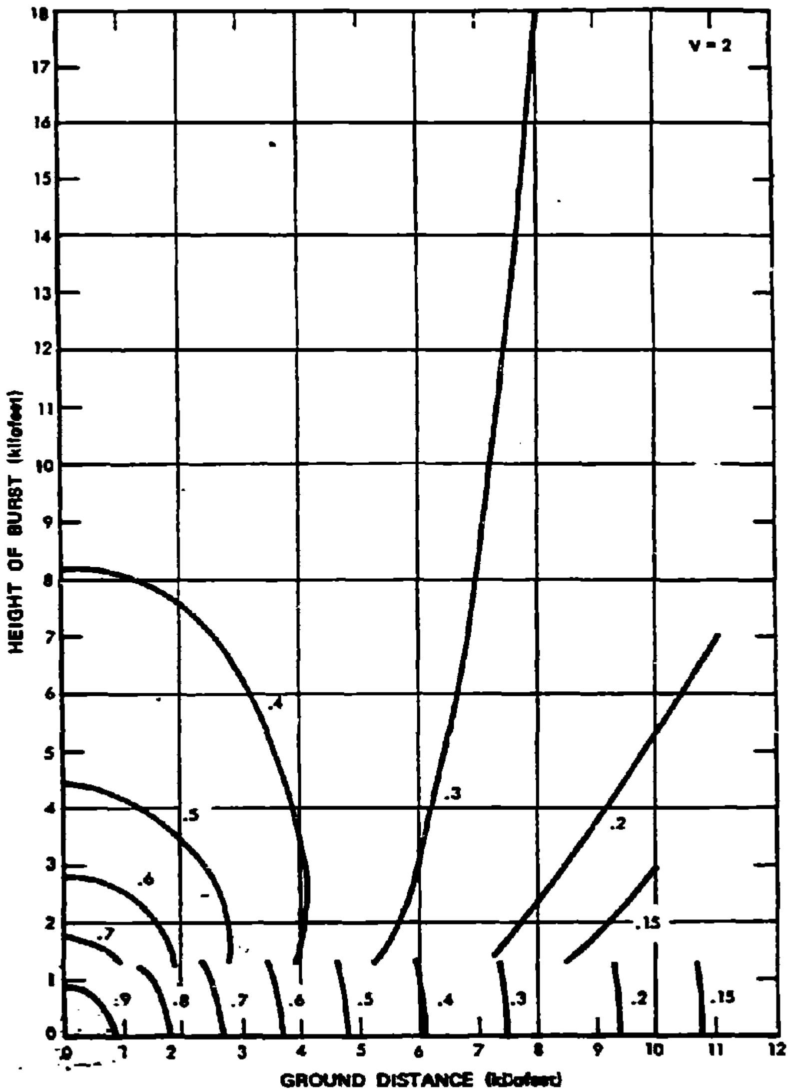

Figure 3-6. [redacted] Transmittance to a Target on the Ground on a Clear Day (Visual Range = 2 Miles) [redacted]

[redacted]

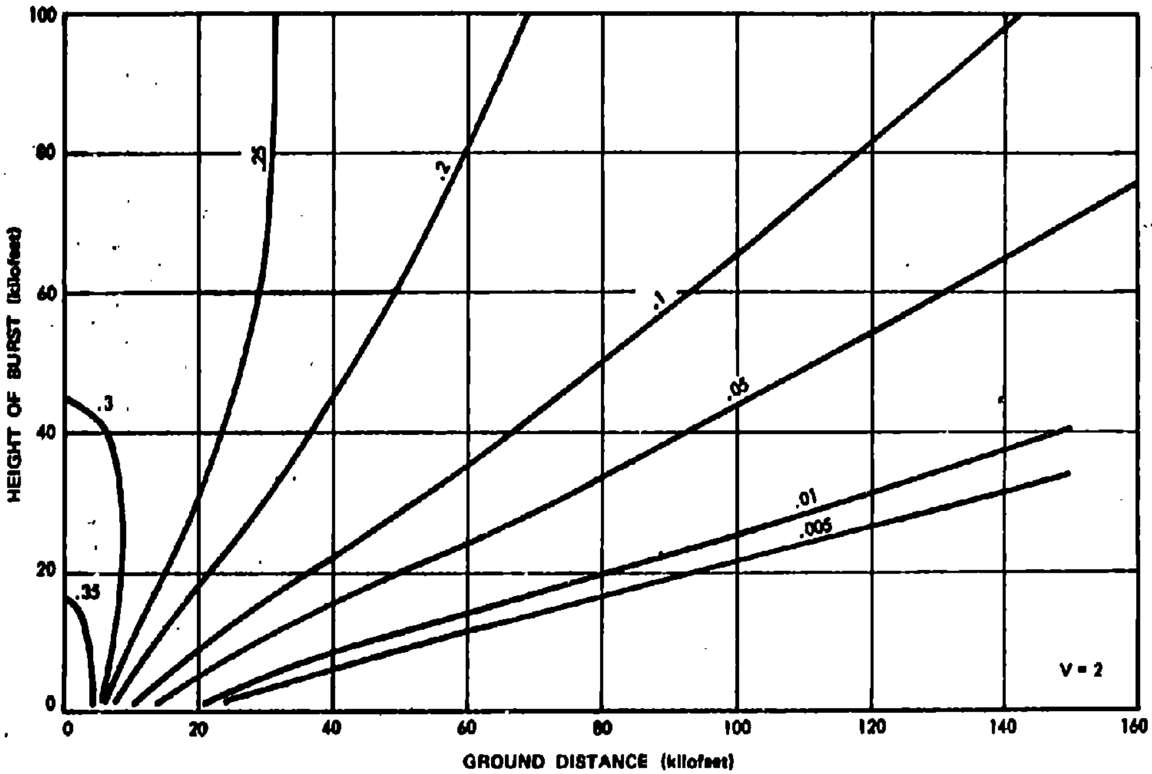

Figure 3-7. [redacted] Transmittance to a Target on the Ground on a Clear Day (Visual Range = 2 Miles) [redacted]

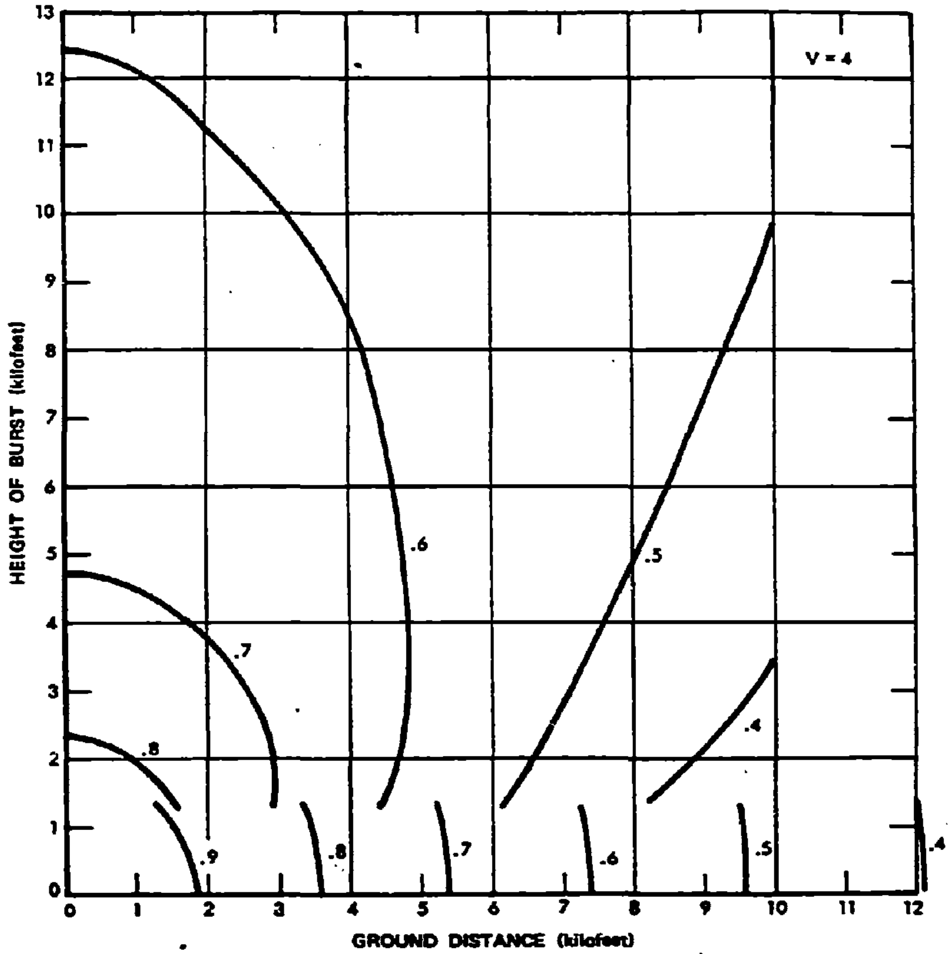

Figure 3-8. [redacted] Transmittance to a Target on the Ground on a Clear Day (Visual Range = 4 Miles) [redacted]

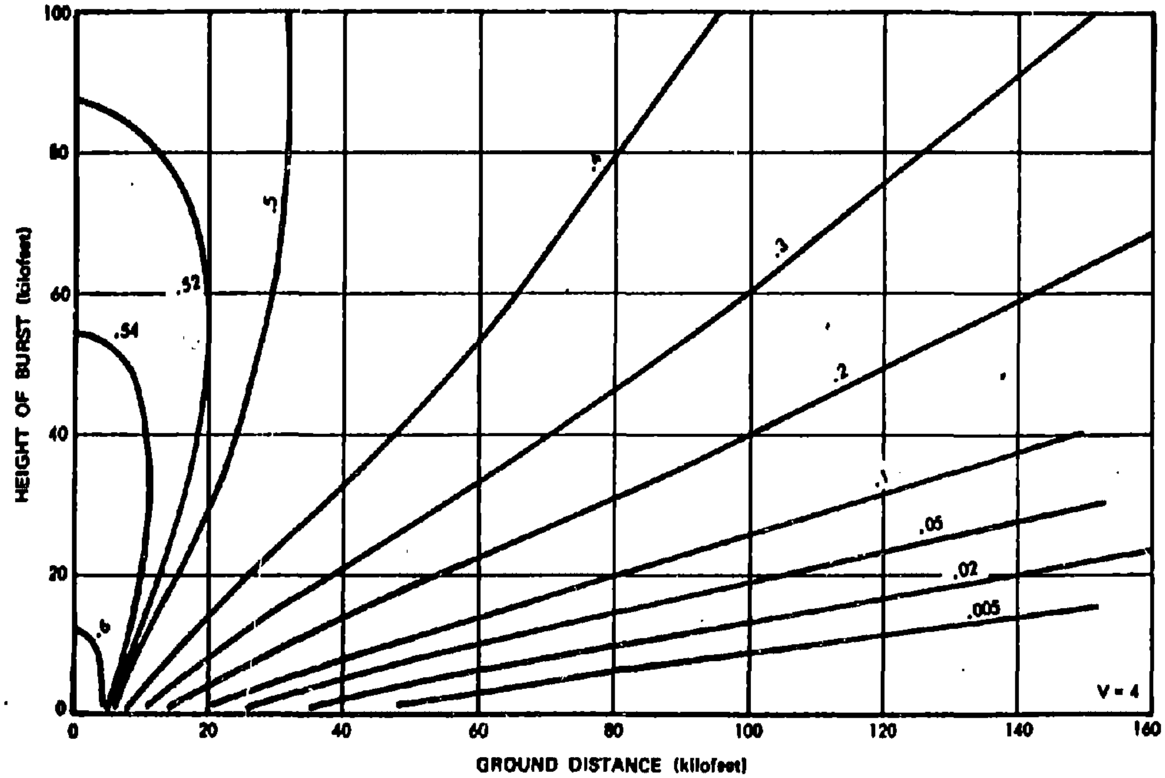

Figure 3-9. [redacted] Transmittance to a Target on the Ground on a Clear Day (Visual Range = 4 Miles) [redacted]

[redacted]

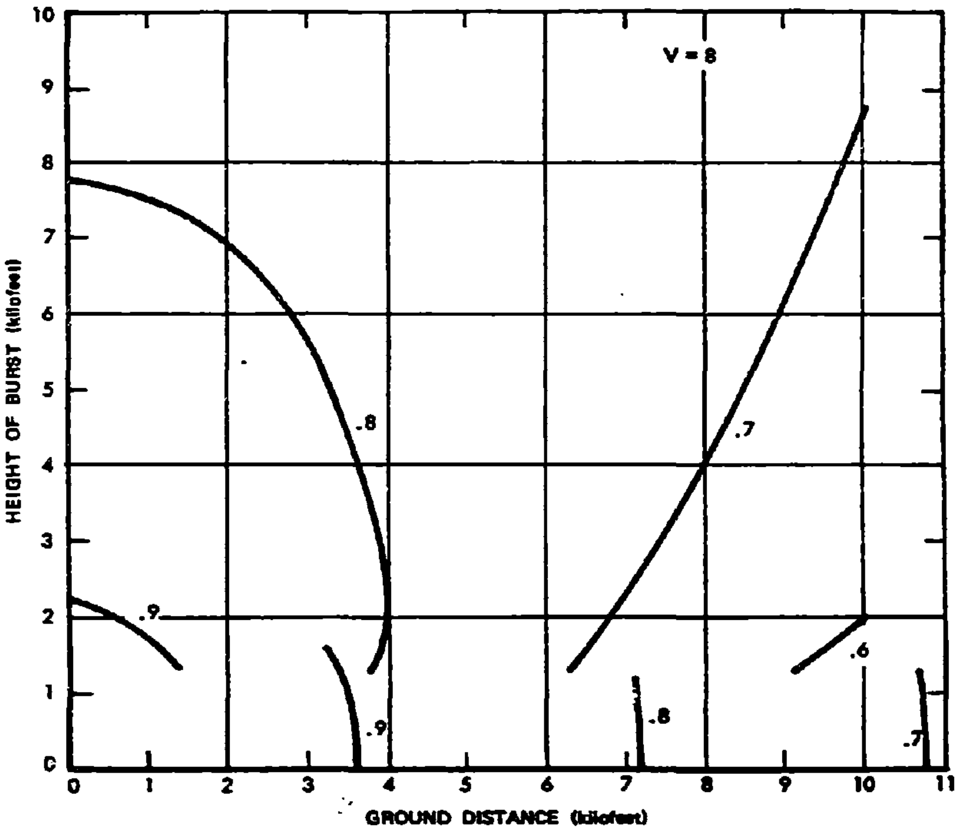

Figure 3-10. [redacted] Transmittance to a Target on the Ground on a Clear Day (Visual Range = 8 Miles) [redacted]

[redacted]

[redacted]

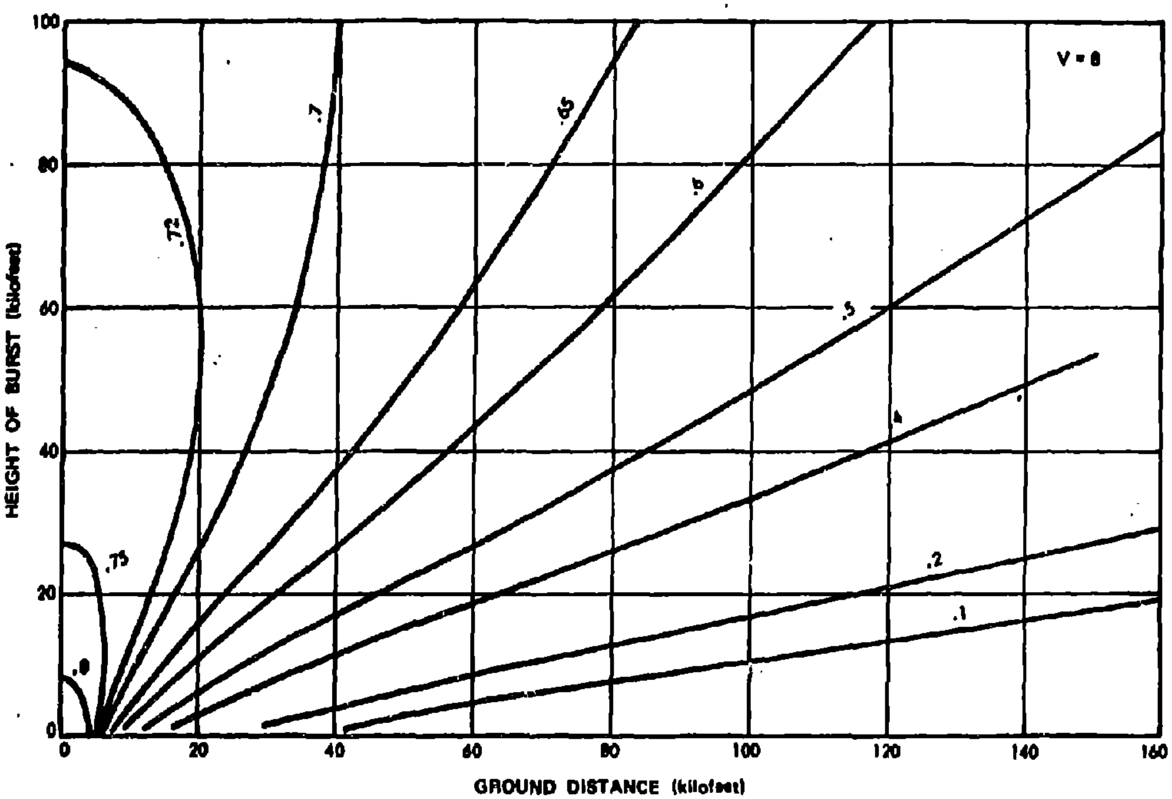

Figure 3-11. [redacted] Transmittance to a Target on the Ground on a Clear Day (Visual Range = 8 Miles) [redacted]

[redacted]

[redacted]

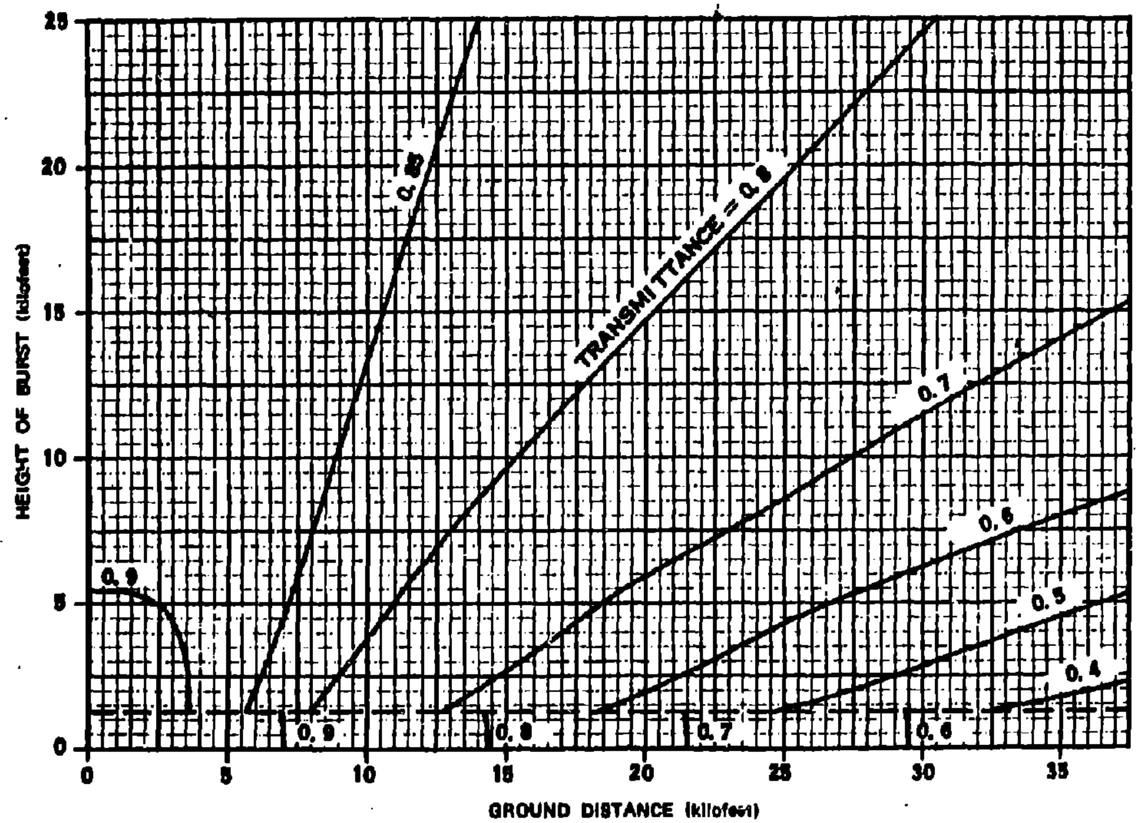

Figure 3-12. [redacted] Transmittance to a Target on the Ground on a Clear Day (Visual Range = 16 Miles) [redacted]

[redacted]

[redacted]

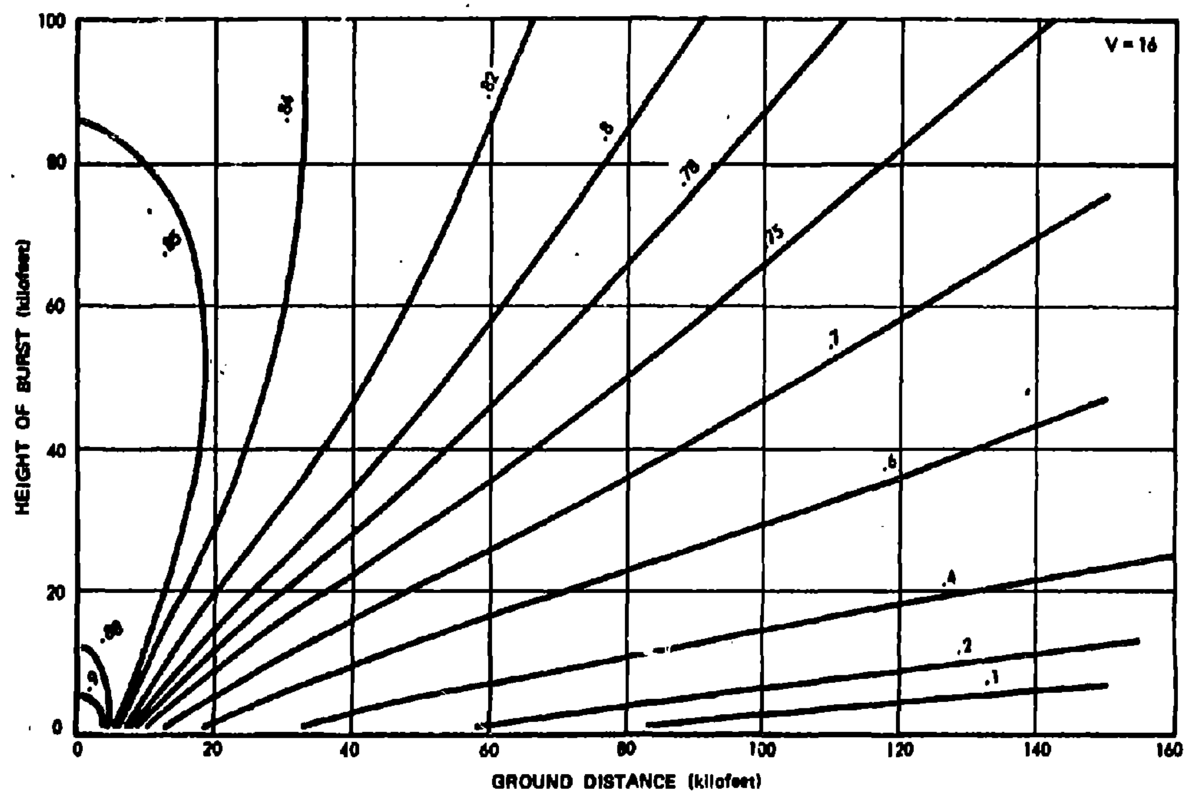

Figure 3-13. [redacted] Transmittance to a Target on the Ground on a Clear Day (Visual Range = 16 Miles) [redacted]

[redacted]

[redacted]

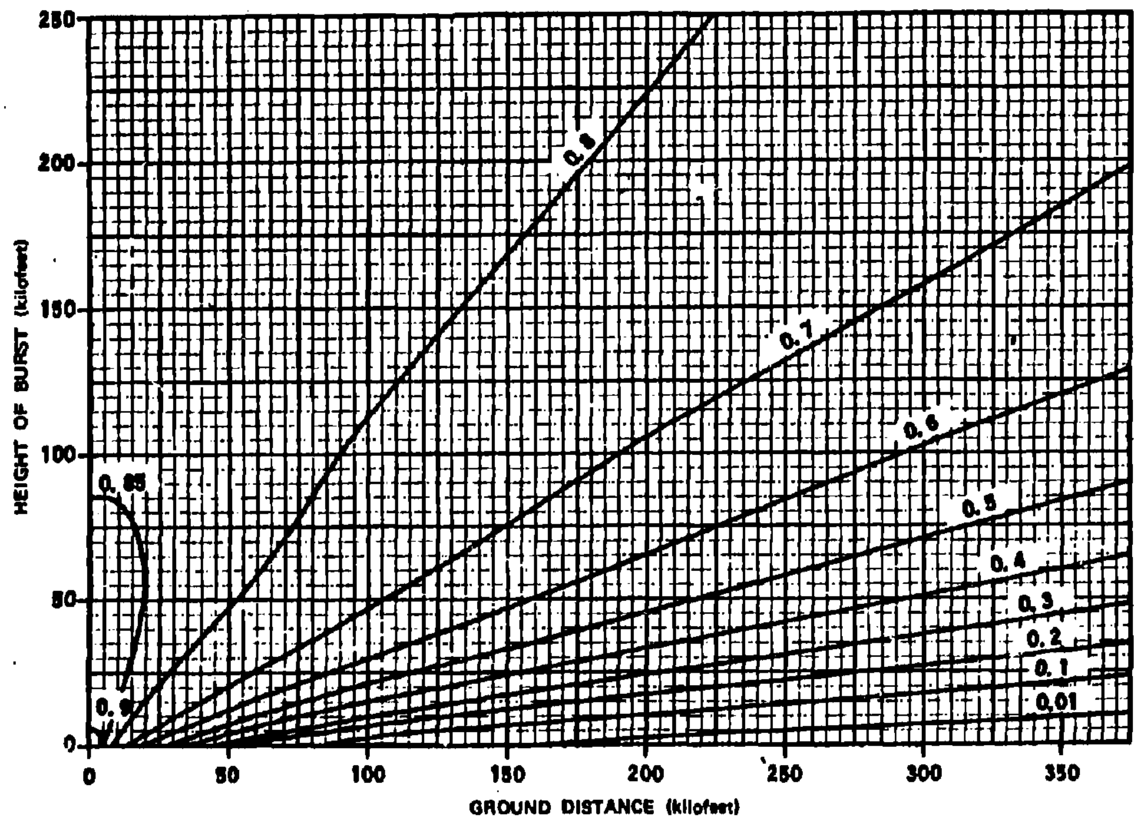

Figure 3-13a. [redacted] Transmittance to a Target on the Ground on a Clear Day (Visual Range = 16 Miles) [redacted]

[redacted]

[redacted]

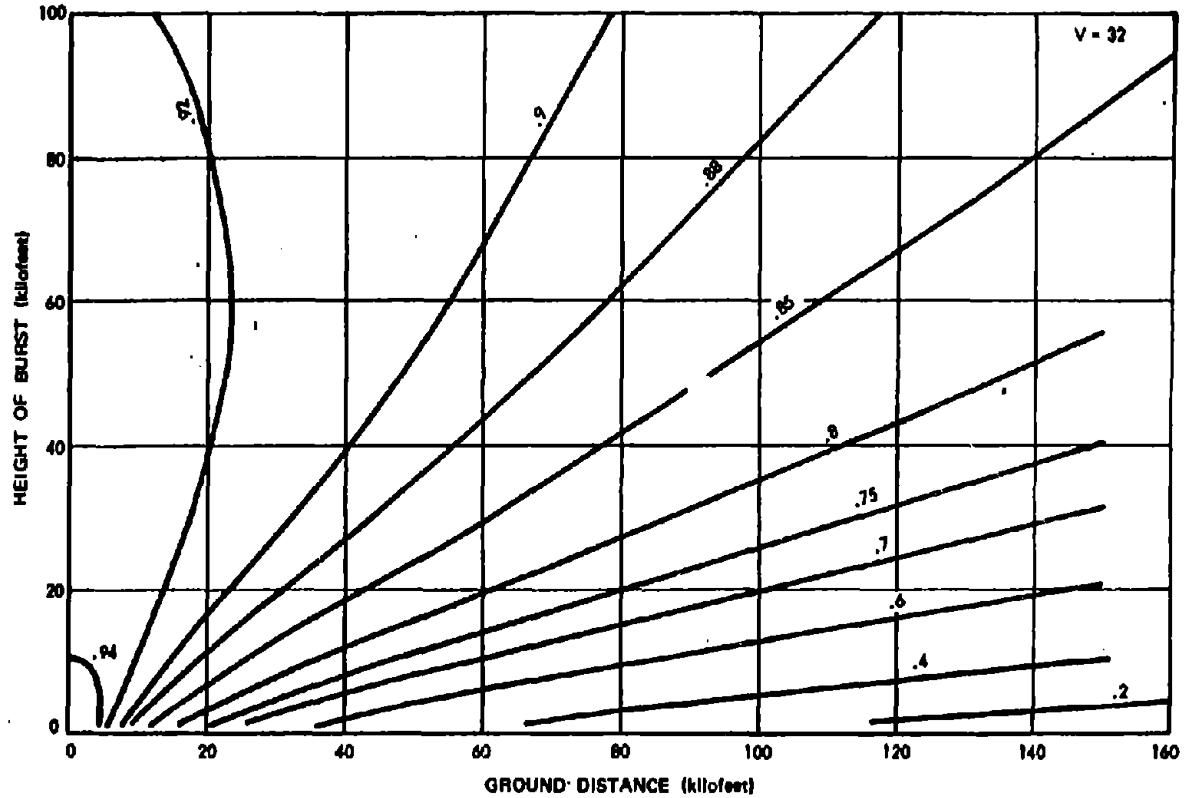

Figure 3-14. [redacted] Transmittance to a Target on the Ground on a Clear Day (Visual Range = 32 Miles) [redacted]

[redacted]

[redacted] Figure 3-15 shows transmittance data for bursts above 100,000 feet. As mentioned above, transmittance above this altitude depends only on the elevation angle. For convenience, Figure 3-15 shows the transmittance as a function of the ratio of slant range to height of burst as well as the elevation angle.

3-5 Effects of Clouds and Reflecting Surfaces [redacted]

[redacted] The model atmospheres are cloudless, and all have the same basic pattern of transparency as a function of altitude. When the actual atmosphere does not conform to these limitations, the calculation procedure must be modified.

[redacted] If a cloud layer is present and the burst is above the clouds, a transmission modifying factor is used to account for the attenuation produced by the cloud layer. Table 3-1 provides a list of transmission correction factors in terms of the appearance of the daytime sky. Transmittance is calculated as though the air were clear and no cloud layer were present, and the result is multiplied by the correction factor obtained from the table.*

[redacted] Table 3-1 suggests two ways to calculate the transmittance for a high-altitude burst (high enough to be in clear air, above the haze and clouds) when the haze (or fog) extends to the ground. For example, if a medium haze exists, a 4 mile visual range could be assumed, and from Figure 3-9 the transmittance of a high altitude overhead burst would be 0.51. Alternatively, the transmittance of a typical clear day (visual range = 16 miles), 0.85, could be used as a starting point. This with the modifying factor for medium haze, 0.5, gives a transmittance value of about 0.43. The discrepancy is within the uncertainty of the calculation.

[redacted] Judgment must be used to determine whether a transmittance calculation should be based on visual range or on sky appearance. If the burst is directly over the target and high enough to be above cloudy or hazy air, sky conditions provide the better basis for the calculation. If the burst is at a low height and the target is at a long ground distance, visual range is preferred. When the situation is less clear, looking through the atmosphere may suggest which criterion is the more representative of conditions along the path from the burst to the target.

[redacted] The transmission modifying factors ordinarily should be used with the HOB curves for 16 mile visual range, otherwise the attenuation of the atmosphere is counted twice.

[redacted] Since a cloud layer appears thicker when the sun is low in the sky, cloud cover estimates made under this condition should be modified by taking the type listed just above the cloud description that fits the observed conditions best. Similarly, when the elevation angle of the burst is below 30°, the effect of a given cloud cover will be greater than if the burst were more nearly above the target area. In this case it is appropriate to take the transmission modifying factor just below the one that would ordinarily be selected.

[redacted] This procedure is based on the similarity between the solar spectrum and the spectrum of thermal radiation from a fireball. Although the spectra are by no means identical, the ability of the atmosphere to transmit solar radiation often is the best available indication of its ability to transmit thermal energy. The appearance of the sky is, of course, an indication of its effect on light from the sun.

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*[redacted] It might appear that thermal radiation that passes through a cloud at an angle with the vertical would be attenuated more than the same radiation would be if it passed through the cloud vertically; however, the radiation does not follow a line-of-sight path but follows randomly directed paths characteristic of diffusion. The attenuation depends on the angle of the line-of-sight path to some extent, but the dependence is not strong, and radiation will penetrate a thick cloud about equally well regardless of the angle at which it enters.

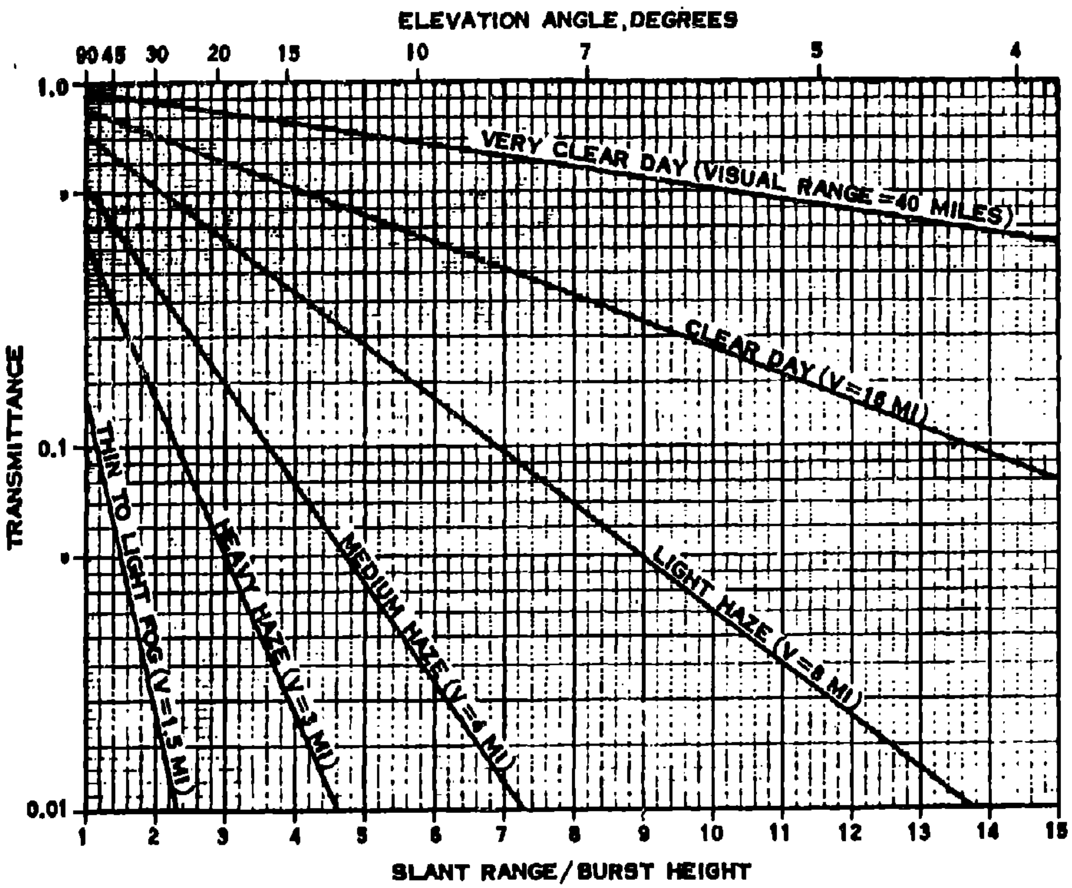

Figure 3-15. [redacted] Atmospheric Transmittance for Thermal Radiation from High Altitude Nuclear Bursts (Height of Burst > 100 kft) [redacted]

[redacted]

Table 3-1. [redacted] Modifying Factors for Transmission Under Various Atmospheric Conditions [redacted]

If Haze or Fog Layer Extends to the Surface		If Haze or Cloud Layer is Overhead		
Type	Probable Visual Range (miles)	Type	Description	Transmission Modifying Factor
Very clear	32.0	Very clear	This condition rare except at high-altitude locations.	1.1–1.0
Clear	16.0	Clear	Sky deep blue. Shadows distinct, dark.	1.0–0.9
Light haze	8.0	Light haze	Sky white; dazzling near sun. Shadows visible, gray.	0.9–0.6
Medium haze	4.0	Medium haze	Sky bright grayish-white. View sun without serious discomfort. Shadows visible but faint.	0.6–0.4
Heavy haze	3.0	Heavy haze	Sky dull gray-white. Sun's disc just visible. Shadows barely discernible.	0.5–0.3
Thin fog	1.5	Light cloud	Sky light gray with maximum luminance around sun. Sun's disc not visible, no shadows.	0.4–0.2
Light fog	0.8	Medium cloud	Sky dull gray with maximum luminance at zenith.	0.3–0.1
–	–	Heavy cloud	Sky dark gray; brightness pattern gives no indication of sun's position.	0.2–0.06
–	–	Dense cloud	The low luminance level suggests the approach of nightfall. Gloomy.	0.1–0.02

[redacted]

[redacted]

[redacted] If a cloud layer lies above the burst, it will scatter thermal energy toward the ground. The calculated value of transmittance should be multiplied by the modifying factor 1.5 when a cloud layer is above the explosion.

[redacted] If the burst is between cloud layers, the upper layer will act as a reflector and the lower layer as an attenuator. If the two layers are equally thick, as much thermal energy will emerge from the bottom of the lower cloud layer as will emerge from the top of the upper layer. In most situations of this type, the cloud structure cannot be determined well enough to make detailed transport calculations meaningful; consequently, systematic calculation procedures for this case have not been developed. However, the procedures already described may be used to set approximate limits on the values of transmittance that may apply.

[redacted] Similar problems arise when a broken cloud cover lies between the burst and the target. Whether the target will be in the shadow of a cloud at the time of burst is, in most practical situations, impossible to determine, and the results of transmittance calculation become much more uncertain. If the individual clouds are sufficiently thick that they do not reveal the location of the sun by a local bright area, and if they are spaced sufficiently close that they shade each other (i.e., so that some of the cloud areas appear dark gray), transmittance to targets shaded from direct radiation from the fireball will be roughly 20 percent of the transmittance calculated for a cloudless atmosphere.

[redacted] When any cloud or haze layer listed in Table 3-1 is in contact with the surface, that layer has a most probable value of visual range associated with it. Under these conditions, the appearance of the sky may be used, in the absence of more direct measurements, to estimate visual range. Table 3-1 includes a rough assignment of visual range values in terms of the appearance of the sky.

[redacted] An additional modifying factor relates to surface albedo, which is the reflection coefficient of the surface of the earth. Most surfaces, including water and desert areas, have low albedos (usually 25 percent or less). Only surfaces such as snow and white sand are in the high albedo class. These latter surfaces enhance thermal radiation because they can reflect energy directly toward the target and also because they reflect energy into the atmosphere, where some of it is scattered back toward the target. When such a surface is present, the calculated transmittance is multiplied by 1.5. If the burst is between a cloud layer and a high albedo surface, the enhancement factor is applied twice, giving a factor of 2.25.

3-6 Transmittance to Targets Above the Surface [redacted]

[redacted] Transmittance to targets above the surface (e.g., aircraft in flight) may be calculated by using an equation similar to that given in paragraph 3-4 for the model atmosphere above one-quarter mile,

$$T = e^{-\Delta\tau(h)\ \frac{16}{V}\ \frac{R}{\Delta h}}$$

where $\Delta\tau(h)$ is the absolute value of the difference between $\tau(h)$ at burst altitude and $\tau(h)$ at target altitude (values of $\tau(h)$ can be obtained from Figure 3-2), Δh is the absolute value of the altitude difference between the burst and the target, V is visual range at the surface, and R is slant range between burst and target.

[redacted] If the burst and target altitudes are equal, the exponent in the equation becomes indeterminate. An estimate may be obtained in this case by increasing burst altitude a small amount, decreasing target altitude the same amount, and holding slant range constant. Estimates obtained from this equation must be regarded as very rough approximations to actual transmittance.

[redacted]

[redacted]

Problem 3-3. Calculation of Transmittance

[redacted] Table 3-1 provides descriptions of various atmospheric conditions from which visual range may be estimated. The table also provides transmission modifying factors to be applied to the transmittance values for a 16 mile visual range when appropriate. Conditions under which the appearance of the sky should be used rather than the measured or estimated ground level visual range to determine transmittance are described in paragraph 3-5.

[redacted] *Example 1* [redacted]

Given: A nuclear explosion at an altitude of 5,000 feet. The appearance of the sky suggests a light haze atmosphere.

Find: The transmittance to a target on the surface 50,000 feet from ground zero.

Solution: Since the line of sight from the burst to the target is low and nearly horizontal, visual range rather than sky appearance would provide a better criterion for selecting a model atmosphere. Nevertheless, this problem must be solved on the basis of sky appearance, because a direct visual range measurement is not available. From Table 3-1, a light haze condition corresponds to a visual range of 8 miles.

Answer: From Figure 3-11, the transmittance is 0.15. No definite tolerance can be placed on this value of transmittance, and it must be regarded as a rough estimate.

[redacted] *Example 2* [redacted]

Given: A nuclear explosion at an altitude of 30,000 feet. The visual range is 6 miles, and the sky appearance fits the medium cloud condition. The time is one hour before sunset, and the ground is covered with snow.

Find: The transmittance to a target on the surface 10,000 feet from ground zero.

Solution: Since the burst is nearly over the target and is sufficiently high that it probably is above most of the haze and clouds, the sky conditions provide the best indication of transmittance. Therefore, the visual range will be ignored in the solution. As a result of the low elevation angle of the sun, the cloud layer appears to be thicker than it actually is. Therefore, the transmission modifying factor for light cloud conditions should be used rather than medium cloud conditions.

Answer: From Figure 3-13, transmittance on a clear day (16 mile visual range) would be 0.86. From Table 3-1, the transmission modifying factor for light cloud conditions is between 0.2 and 0.4. Reflection from the snow covered surface requires an additional correction factor of 1.5. The calculated transmittance therefore lies between

$$(0.2)(1.5)(0.86) = 0.26,$$

and

$$(0.4)(1.5)(0.86) = 0.52.$$

[redacted] *Reliability* [redacted]

[redacted] In general, transmittance calculations are most reliable when transmittance is high and when the atmosphere is relatively clear. A tolerance of ±30 percent is assigned when transmittance exceeds 0.1 and when visual range is 5 miles or greater. This tolerance is based on comparisons between transmittance calculations made by the methods of several different investigators. When reflection from snow cover or an overhead cloud cover must be considered, the uncertainty rises to ±60 percent.

[redacted] Comparisons of calculated values with data from full scale nuclear tests show uncertainty that basically relates to the product fT, since thermal partition and transmittance cannot be measured independently. When transmittance

[redacted]

[redacted] exceeds 0.1 and visual range exceeds 5 miles, the tolerance on thermal partition f accounts for all of the uncertainty in the fT product. No additional tolerance on T is required. When reflecting surfaces are present or when visual range drops below 5 miles, an additional ±30 percent tolerance should be applied.

[redacted] No reliability estimate is assigned to calculated transmittances below 0.1. At these low values, transmittance estimates become increasingly uncertain, and errors may rise to factors of 2-10.

[redacted] Errors in the estimation of visual range also can affect the error in the calculation of transmittance. If a visual range of 3 miles is estimated as 2 miles, which is not an unreasonable error, the percent error in transmittance rises rapidly as the transmittance drops to low values.

[redacted] Additional errors are produced by approximations in the calculation procedure. These errors tend to be small when transmittance is high and large when transmittance is low. Three approximations are made in transmittance calculations.

[redacted] First, a single parameter, visual range, serves as the basis for transmittance calculations in cloudless atmospheres. Although visual range at the surface is only one of the parameters required to specify the transmitting properties of the region between the burst and the target, it is one of the very few parameters that can be observed directly from the ground. Other parameters necessary to define the atmosphere completely are supplied by a set of model atmospheres that include the measured visual range at the surface and an increasing transparency with increasing altitude. This change in transparency with altitude is chosen to match the changes that occur in real atmospheres under typical conditions; however, there is no assurance that the model atmosphere is a particularly good match to any single real atmosphere.

[redacted] Second, the transport of thermal energy through these model atmospheres is calculated from empirical equations confirmed by experimental data. The results of more accurate computational procedures are expected at some future date.

[redacted] Third, the model atmospheres are cloudless. Cloud effects are accounted for by correction factors that modify the transmittance calculated for a cloudless atmosphere. An empirical treatment of some kind is unavoidable; cloud effects are too complex to be treated rigorously.

[redacted] Any of these sources of error can, under certain conditions, cause the calculated transmittance to be wrong by a factor of 10 or more, but these extremely high errors appear when the atmosphere attenuates thermal energy from the fireball strongly and therefore when thermal effects are unlikely to be as important as other effects such as blast.

3-7 Visual Range [redacted]

[redacted] Ordinarily, the purpose of visibility measurements is to determine the ability of an observer to see through the atmosphere; such a measurement may determine the approximate distance at which a pilot can recognize a runway. In the study of thermal effects, visibility measurements are useful because they indicate the transparency of the atmosphere and its ability to transmit thermal radiation. The model atmosphere that should be used in a particular transmittance calculation is selected on the basis of daytime visual range.

[redacted] The term *visual range* as used in this chapter is synonymous with *daytime visibility* as commonly measured at weather stations. Although "visibility" is a more widely used term than "visual range," the latter is used in this chapter because it indicates that the quantity being discussed is a distance and not a measure of the clarity with which a particular object can be seen. Visual range is defined as the distance at which a dark object silhouetted against the sky is visible and recognizable. It is commonly measured in statute miles.

[redacted] Two factors make it advisable for the person who must develop the ability to make weapon effects calculations in tactical situations to understand the procedures for measuring visual range. First, he will not always have access to weather station information. Second, he may wish to question the information he obtains from weather stations. For the usual purposes of visual range measurements, underestimates of this range are less serious errors than are overestimates. For troop safety calculations, the opposite is true. Some meteorologists, not in the habit of thinking in terms of weapons effects, may shade their estimates incorrectly.

[redacted] At the visual range, all objects appear so nearly alike in both brightness and color that a dark object silhouetted against the sky is barely recognizable. This reduction in contrast may be described quantitatively in terms of the brightness B of an object and the brightness of B' of the background. Contrast is defined as the ratio

$$C = \frac{B - B'}{B'}$$

If the object is darker than its background, the contrast is negative, reaching -1 for a perfectly black object. On the other hand, lights have very large positive values of contrast at night.

[redacted] A hypothetical example illustrates the problems of estimating visual range and the accuracy that may be expected from such estimates. Table 3-2 shows a series of values calculated for the condition that the fifth pole of a row of telephone poles closely spaced in a uniform fog is at the visual range as it would be

Table 3-2. [redacted] Contrast Ratio for a Series of Black Telephone Poles in a Fog: Visual Range = 500 Feet [redacted].

Pole Number	Distance (feet)	Contrast Ratio
1	100	0.56
2	200	0.31
3	300	0.18
4	400	0.098
5	500	0.055
6	600	0.031
7	700	0.017
8	800	0.010

[redacted] measured by a transmissometer.* If the poles have a dark color, the inherent contrast of each pole with its background may be assumed to be nearly 100 percent. The contrast, as seen by the observer is given in the last column, and is, by definition, 0.055 at the visual range.†

[redacted] What an observer sees may be affected by factors such as the uniformity of the fog layer. The first three or four poles are distinct, the fog has changed the apparent color of even the first pole to gray. The fourth pole is sufficiently distinct that if the cross arms are of lighter wood than the pole itself the difference in color is discernible. The fifth pole, at the visual range, is little more than a shadow, but it would be visible instantly and would be recognized as a telephone pole even if it were standing alone.

[redacted] An observer looking at the sixth pole standing alone probably would see it if he knew where to look, but he might question its identity. Although the line separating the image of the pole from its background is sharp, the faintness of the contrast makes the outline appear slightly blurred.

[redacted] The seventh pole is at approximately the distance known as the *meteorological range*, which is the range that gives a contrast of 0.02 between a black object and the sky. If the pole were standing alone and the observer did not know where to look for it, he very likely would miss it. Meteorological range has often been used as a measure of visual range; it corresponds more closely to the threshold of detection than to the implications of the presently used standard of "visible and recognizable."

[redacted] The eighth pole probably is not visible because of its size. A car parked beside it might be visible, but only if the observer, looking down the row of poles, knows exactly where to look for it. Detection at this contrast level requires a background uniformity that is rare except under laboratory conditions.

[redacted] Many observers would estimate visual range as the distance to the fourth or sixth pole; a few might select the seventh; still fewer, the third. As Table 3-2 shows, the error in range that this uncertainty produces is not excessive.

[redacted] The factors that would lead some observers to select the fourth pole may include more than overly conscientious application of the "visible and recognizable" rule. The fifth pole is only about 1/4 as wide as the ideal distance marker (which should subtend an angle of

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*[redacted] A transmissometer is an instrument designed to measure light transmission characteristics of the atmosphere. It consists of a light and a detector separated by a baseline of either 500 or 750 feet. The transmissometer reading is called transmissivity. It is the ratio of the light received at the detector to the light that would be received if the air were perfectly transparent. The transmissivity defines the ability of a direct beam of light to penetrate a specified distance (the transmissometer baseline) through the atmosphere. The transmittance, as used in this chapter, defines the ability of radiant energy to pass through the atmosphere between a nuclear explosion and a target either directly or by scattering.

†[redacted] The visual range may be defined as the range at which the apparent contrast between a black object and its sky background is reduced to 5-1/2 percent or as the range at which a beam of light is reduced to 5-1/2 percent of the intensity it would have in a transparent atmosphere. Light from the sky generally appears to come from the region behind objects on the horizon, but air light originating beyond an object at the visual range actually contributes little to the sky brightness that the observer sees. All but 5-1/2 percent of this distant light is scattered out of the line of sight before it reaches the observer. The air between the object and the observer contributes as much to the apparent brightness of the object as it does to the brightness of the sky, but, if the object is black, it fails to contribute the 5-1/2 percent of total sky brightness that reaches the observer from the air beyond the object. The contrast to the observer is reduced from 100 percent to 5-1/2 percent. These conclusions are strictly correct: if the brightness and color of the sky as seen at the object is the same as the brightness and color of the sky as the observer sees it; if the atmosphere is not hazy, i.e., if the atmosphere is clear enough that the scattering cross section varies appreciably with wavelength and contrast is reduced to 5-1/2 percent for all colors; absorption of light is assumed negligible.

[redacted] In practice, these three restrictions usually may be ignored. The errors they introduce are in most cases no more serious than other problems (such as nonuniformities in the atmosphere) that limit the precision of visual range measurements.

[redacted] at least 1/2°), and for this reason it may not appear to be as distinct as a larger object would.

[redacted] Additional factors that could cause an observer to underestimate visual range can occur when the seeing conditions are different from those assumed in this example. For example, the fog was assumed to be perfectly uniform. Actually, the atmosphere near the surface over land is rarely uniform, and patches of haze that can be misjudged for distant objects are common. Shimmer, an optical effect similar to the heat waves observed over a metal object on a sunny summer day, can distort images of distant objects and can reduce the apparent visual range even though the air is clear.

[redacted] An observer who uses a distant hill for a range marker may be inclined to overestimate visual range. This is particularly true if he knows, perhaps from the pattern formed by closer hills, exactly where to look. Aided by such landmarks, he may detect so many details of the familiar outline that, to him, the hill is definitely "visible and recognizable." The observer, if he is unsure of the mark, should ask himself whether he sees the hill clearly enough that *conspicuous* surface features (e.g., patches of trees separated by large areas of light-colored, vegetation-free rock) would be faintly discernible, even though such features may not actually be present. He should also ask whether an observer unfamiliar with the terrain would be reasonably sure that he was looking at a hill instead of cloud structure near the horizon. If the answers to these questions are "yes," he should judge the hill within the visual range.

[redacted] Distance markers that are appreciably easier or harder to see than the standard dark-colored marker should be avoided if possible, since they lead to inaccurate measurements of visual range. A snow-covered mountain is likely to be an unreliable marker for two reasons: If the peak is at a high altitude, the observer sees it through air that is usually clearer than the air along a line of sight closer to the surface. Also, under strong illumination the snow is visible from a greater distance than darker portions of the mountain would be. Either effect can cause an artificially high measured value of visual range, implying a clearer atmosphere than actually exists. On the other hand, the tree-covered base of a mountain is an excellent marker for long visual ranges.

[redacted] Surfaces with high reflection coefficients are not always more easily seen than dark objects. An observer looking in the general direction of the sun may see a white object as darker than the horizon sky, because the side of the object facing the observer is not illuminated strongly. If the angle of the sun is just right, there may be virtually no brightness contrast between a white object and its sky background. On the other hand, the inherent contrast between a very dark object and the sky never varies greatly from 100 percent; therefore, the use of dark objects as distance markers results in reasonably consistent visual range measurements.

[redacted] The observer should be aware of phenomena related to lighting effects. If he is looking at a distance marker that is in the general direction of the sun, the strong forward scattering property of haze particles will make the air light between him and the marker will appear to be particularly bright. This does not affect the distance at which a dark marker can be seen. The sky behind the marker is similarly bright, and the apparent contrast between the marker and its background is no different than if, for example, the sun were overhead.

[redacted] The preceding discussion provides the user with information that will help him to make accurate estimates of visual range. Much of this information can be condensed to a set of rules.

- Range markers should be as dark as possible. If the reflection coefficient of the

[redacted]

[redacted] marker is more than 30 percent and the sun is behind the plane of the observer, the marker should be avoided.*

- The range marker should be silhouetted against the sky, or its background should be at least half again as far from the observer as is the marker itself. When such a marker is at the visual range, the background will be so nearly obscured that it is indistinguishable from the sky.
- The distance marker should be sufficiently large that increasing its size would not increase the range at which it can be recognized. This requirement is met if the angular size of the marker (vertically and horizontally) is 1/2°, which is the diameter of the full moon. A distance of 5/16 inch on a ruler held at arm's length is an approximate measure of this angle. If shimmer is not a serious problem (if the image is steady), binoculars may make a smaller distance marker usable.
- Distance markers should be available in several directions so that nonuniformities in the atmosphere can be detected.
- When a requirement for visual range measurements in a given area can be anticipated, a map showing usable distance markers should be prepared. It should indicate the range, direction, and identification of each marker. (Heights of hills or tall buildings should also be recorded, because such objects sometimes provide useful indications of cloud height.)
- The altitude of distance markers should be such as to place the line of sight as close as possible to the average ground level.

[redacted] Usually it is necessary to use some markers that fall short of these standards. The markers may be too small or the wrong color, and often no marker will exist at the visual range. In this case the observer must use judgment to decide the visual range that ideal markers would indicate. One important clue is the apparent color of markers that are within the visual range. Clear, undistorted colors indicate that the amount of air light from the intervening air is small, and that objects at considerably greater ranges would be clearly visible.

3-8 Nighttime Visual Range [redacted]

[redacted] The distance at which a person can see a light depends partly on the transparency of the atmosphere. However, it also depends on the state of dark adaptation of the observer, the brightness of the light, and the amount of background produced by whatever other lights may be illuminating the air. Only the first of these four factors concerns the ability of the atmosphere to transmit thermal energy. In general, the variations caused by the last three factors make measurements of nighttime visual range a poorer indication of the transport properties of the atmosphere than measurements of daytime visual range.

[redacted] In the absence of definite changes in the weather, the transparency of the air usually does not change much from day to night. Daytime visual range, which usually can be measured more readily than nighttime visual range, is often the most satisfactory means for estimating the transport properties of the atmosphere the following night.

[redacted] Exceptions occur in regions where the relative humidity exceeds 90 percent in polar regions, and in areas subject to air pollution. In the latter case, the source of pollution (e.g., domestic heating or cooking and industrial exhausts) are likely to vary from day to night. Polluted atmospheres also often produce a haze

*[redacted] The reflection coefficient is about 4 percent for a pine woods and about twice that amount for a deciduous woods. A grassy field, for which the reflection coefficient may exceed 20 percent, is a much less reliable mark.

[redacted]

[redacted]

layer near dawn, particularly when a steep temperature inversion forms near the surface. Such a haze layer may be dense enough to offer some protection from thermal radiation.

[redacted] If nighttime visual ranges must be measured, these ranges should be converted to the equivalent daytime visual ranges. This is necessary because daytime visual range is the parameter on which transmittance calculations are based. Figure 3-16 may be used to convert nighttime ranges to equivalent daytime ranges.

[redacted] Figure 3-16 is based on a large number of observations to determine the distance that a 25 candlepower light (25 candlepower is approximately the output of a 25 watt incandescent lamp) can be seen through various atmospheres. The data were originally taken to correlate transmissometer data with visual range measurements; therefore the seeing conditions would be similar to those existing at airport weather stations.

[redacted] In practice, the 25 candlepower source can be replaced by any light of moderate intensity. In a transparent atmosphere, a 100 watt lamp could be seen about twice as far as a 25 watt lamp, but in an attenuating atmosphere the difference is less. When nighttime visual range is 50,000 feet, the 100 watt lamp could be seen from about 65,000 feet. When nighttime visual range is 5,000 feet, the 100 watt lamp can be seen from about 6,000 feet.

[redacted] APPROXIMATE CALCULATIONS OF RADIANT EXPOSURE [redacted]

[redacted] The procedures described in the preceding subsections permit the calculation of radiant exposure by methods that are as accurate as present knowledge of thermal partition and transmittance allows the information to be presented in a manner suitable for this manual. In many cases, a quicker but less accurate estimation of radiant exposure is desirable. Such an estimate may indicate whether more time consuming calculations are necessary. Figures 3-17a and b are intended for use in such cases.

[redacted] These figures are based on transmittance values for a moderately clear, cloudless atmosphere (visual range = 16 miles) and on thermal partition values for an intermediate value of yield, 200 kt. Transmittances were calculated using the high altitude equation only, and some loss in accuracy is expected for burst heights below 1/4 mile.

[redacted]

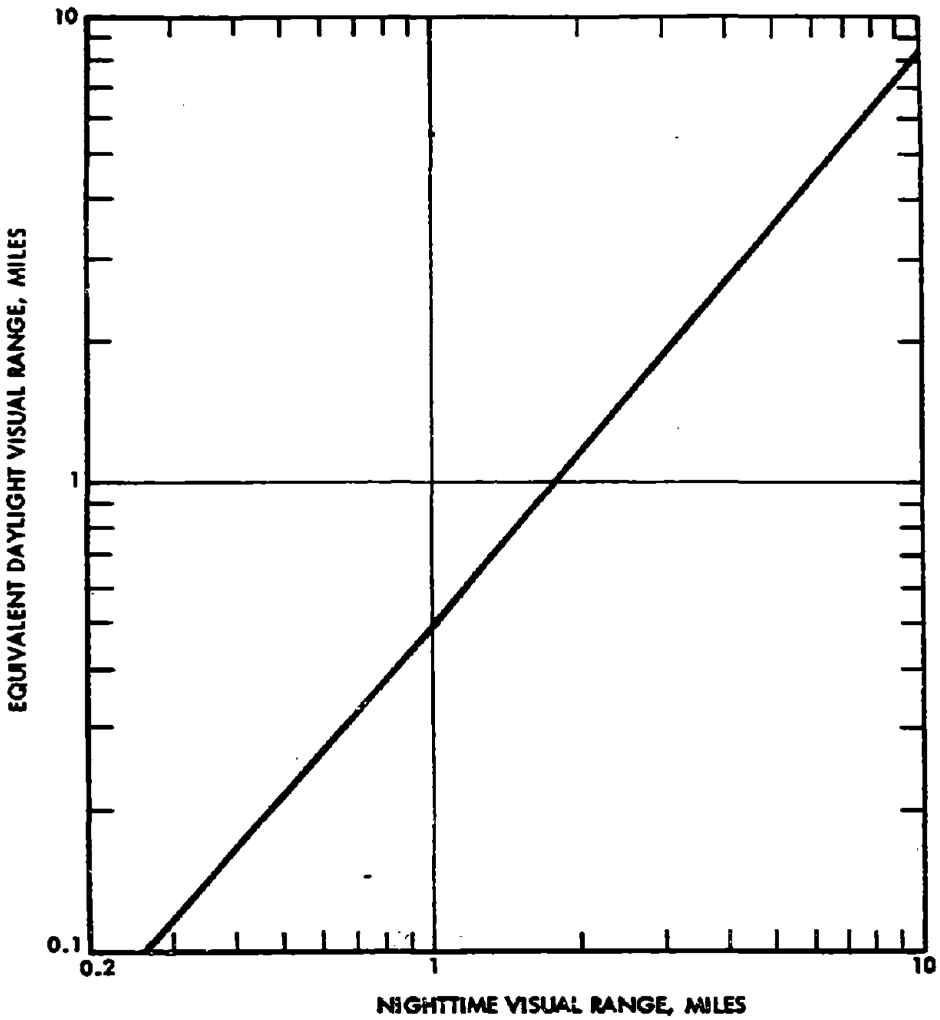

Figure 3-16. [redacted] Equivalent Daytime Visual Range as a Function of Nighttime Visual Range [redacted]

[redacted]

[redacted]

Problem 3-4. Approximate Calculation of Radiant Exposure

[redacted] Figures 3-17a and b show approximate radiant exposure to targets on the surface from a 1 kt explosion as a function of distance from ground zero and height of burst. These curves are based on calculations for a 200 kt explosion under the assumption that the radiant exposure could be scaled to 1 kt directly with yield. Visual range was assumed to be 16 miles.

[redacted] *Scaling.* For yields other than 1 kt, the radiant exposure is

$$Q = Q_1 W,$$

where Q_1 is the radiant exposure for 1 kt obtained from Figure 3-17a or b for the height of burst and ground distance of interest, and Q is the corresponding exposure for W kt.

[redacted] *Example* [redacted]

Given: A 500 kt explosion at an altitude of 30,000 feet.

Find: The radiant exposure on the surface 150,000 feet from ground zero.

Solution: From Figure 3-17b, a 1 kt explosion at an altitude of 30,000 feet will produce a radiant exposure 150,000 feet from ground zero

$$Q_1 = 0.0007 \text{ cal/cm}^2.$$

Answer: The radiant exposure from a 500 kt explosion is

$$Q = Q_1 W = (0.0007)(500) = 0.35 \text{ cal/cm}^2.$$

[redacted] *Reliability:* Radiant exposures from Figures 3-17a and b are approximations. For the assumed atmospheric conditions and burst altitudes below 100 kilofeet, values of radiant exposure obtained from Figures 3-17a and b are estimated to be reliable within ±40 percent. Additional loss of accuracy is expected for bursts below one-quarter mile altitude since the transmittances were calculated with the high altitude equations. The reliability also drops for bursts above 100,000 feet as a result of the uncertainty in the values assumed for thermal partition.

[redacted] *Related Material:* See paragraphs 3-1 through 3-8.

[redacted]

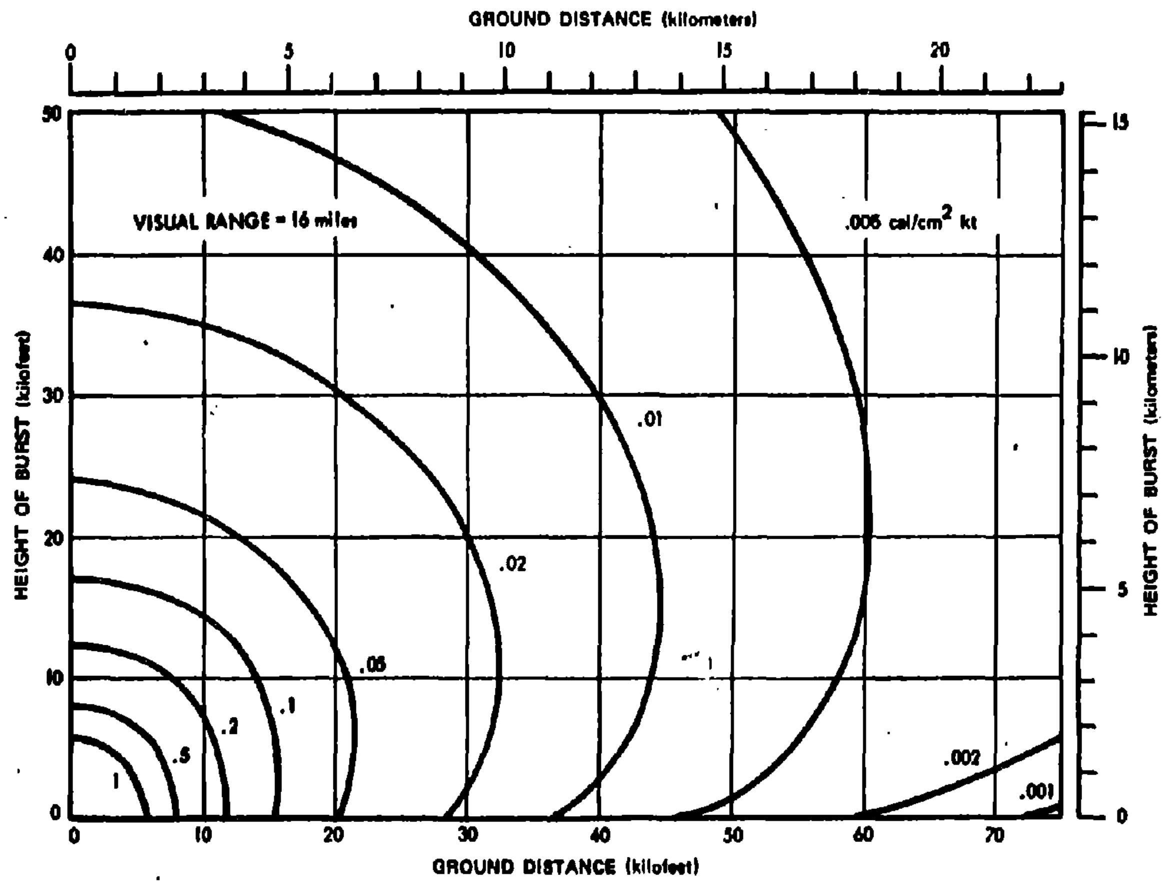

Figure 3-17a. [redacted] Approximate Values of Radiant Exposure Through a Clear Atmosphere [redacted]

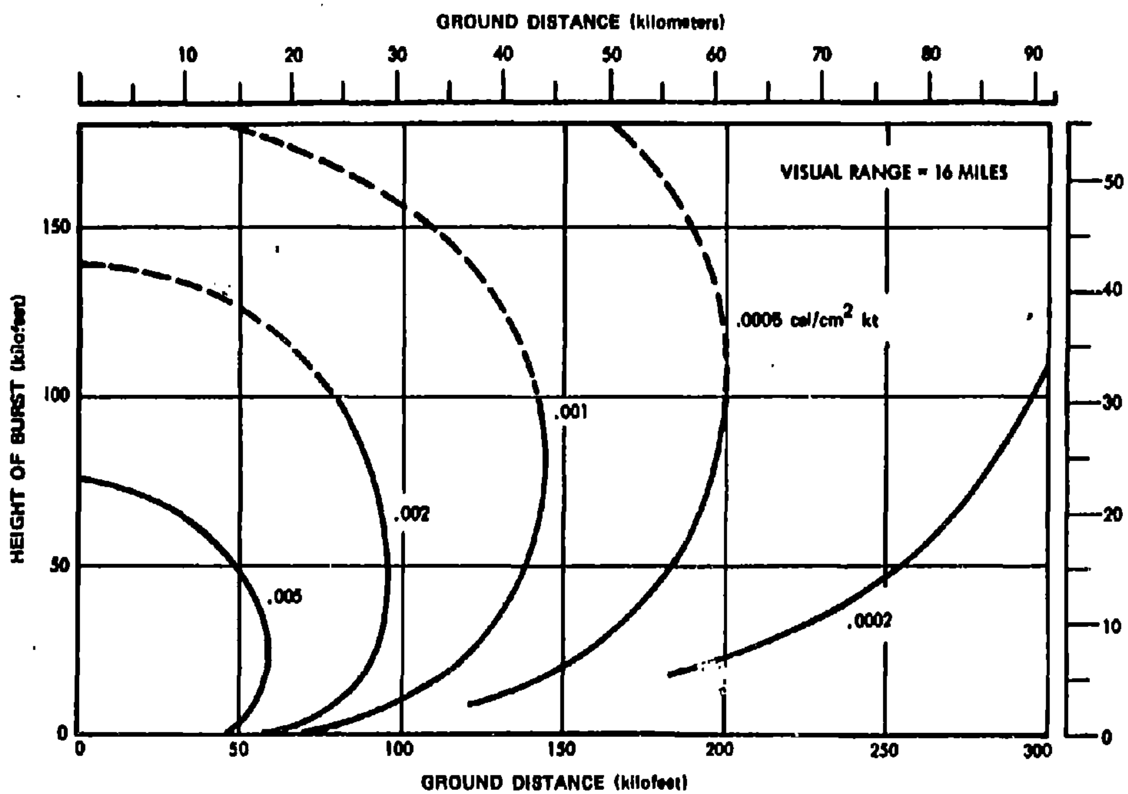

Figure 3-17b. [redacted] Approximate Values of Radiant Exposure Through a Clear Atmosphere [redacted]

[redacted] SURFACE AND SUBSURFACE BURSTS [redacted]

[redacted] Clouds of dust (or spray) partly obscure the fireball of surface bursts and reduce the thermal radiation received by targets on the ground. Even less thermal radiation escapes from underground and underwater bursts. If the burst is deep enough, the earth or water absorbs almost all of the thermal energy; the amount of radiated thermal energy is insignificant.

3-9 Surface Bursts [redacted]

[redacted] The terms contact surface burst, surface burst, and air burst, when used in connection with thermal effects, have meanings similar to those assigned to the same terms in Chapter 2 (see paragraph 2-19). A contact surface burst is one that is no more than 5 $W^{0.3}$ feet above or below the surface. The region between 5 $W^{0.3}$ and 180 $W^{0.4}$ feet (±20 percent for yields between 10 and 100 kt, and ±30 percent for other yields) is called the transition zone, and a burst within this region is a surface burst for purposes of thermal radiation phenomena. Since the fireball is approximately 180 $W^{0.4}$ feet in radius for explosions in the lower atmosphere, a surface burst is any burst above 5 $W^{0.3}$ feet but low enough that the fireball will interact strongly with the surface of the earth. As mentioned in paragraph 3-1, an air burst occurs above 180 $W^{0.4}$ feet.

[redacted] Experimental data indicate that the thermal partition of contact surface bursts is about 0.21. Figure 3-18 assumes a thermal partition of 0.21 for a contact surface burst, assigns the air burst partition (Figure 3-1) to a burst at 180 $W^{0.4}$ feet, and provides intermediate values by linear interpolation. This procedure is arbitrary and is only supported in a general way by experimental data. Points above the dashed line in Figure 3-18 represent air bursts; points below the dashed line are surface bursts. The radiant exposure from surface bursts may be calculated by the formulas given in paragraph 3-2 with the values of thermal partition, f, taken from Figure 3-18.

[redacted] Figure 3-18 describes the fireball as it would be seen by targets on the surface. Clouds of dust would not obscure the fireball from above; consequently, radiant exposure of airborne targets should be calculated on the basis of the thermal partition of free air bursts given in Figure 3-1.

[redacted] Since confinement of the fireball by the surface is roughly equivalent to reflection, the fireball radius for a contact surface burst is larger than that for the same burst in free air. Blast wave theory suggests that the fireball of a contact surface burst as viewed from above might resemble that of a free air burst with a yield of 2.0 W. In fact, determination of fireball yield by hydrodynamic scaling uses the 2.0 W assumption.

3-10 Subsurface Bursts [redacted]

[redacted] Two effects reduce the amount of thermal energy radiated by the nuclear explosions below the surface of the earth: a large amount of thermal energy is absorbed in fusing and vaporizing the earth; and the fireball that does develop above the surface is obscured to a great extent by earth that is thrown from the crater. Even relatively shallow underground bursts throw dirt up as a cone shaped cloud that screens surface targets from thermal radiation effectively.

[redacted] Since surface reactions are complex and different types of surfaces react in different ways, the effects of underground bursts are extremely variable. As a result of these complexities as well as the fact that thermal effects from underground bursts usually are unimportant compared to other effects, methods for predicting thermal partition have not been developed for underground bursts.

[redacted]

[redacted] Underwater bursts are similar to underground bursts in that thermal radiation is greatly reduced by the heat absorbed by the water and by the screening effect of water thrown from the crater. Thermal effects usually are insignificant. For example, a 20 kt burst in 90 feet of water produced negligible thermal radiation.

[redacted]

[redacted]

Problem 3-5. Calculation of Thermal Partition for a Surface Burst

[redacted] Figure 3-18 contains a family of curves that provide an effective thermal partition for surface targets from nuclear explosions that occur at heights of burst greater than 5 $W^{0.3}$ feet and less than 180 $W^{0.4}$ feet. A thermal partition of 0.21 should be used for surface targets for bursts 5 $W^{0.3}$ feet above or below the surface. Thermal partition for targets directly above the burst should be obtained from Figure 3-1 or from the upper portion (above the dashed line) of Figure 3-18.

[redacted] *Example* [redacted]

Given: A 500 kt explosion at a height of burst of 300 feet.

Find: The effective thermal partition.

Solution: From Figure 3-18, the effective thermal partition is 0.24.

Answer: The effective thermal partition for a surface target is 0.24. The effective thermal partition for a target directly above the burst is 0.45 (from Figure 3-1, or from the intersection of the dashed line in Figure 3-18 with a yield of 500 kt). The thermal partition for targets at intermediate altitudes would fall between these values. As a result of the uncertainties (see Reliability), the thermal partition for surface targets could fall between 0.44 and 0.1, and the thermal partition for targets directly over the burst could fall between 0.65 and 0.25.

[redacted] *Reliability:* Interaction of the fireball with the surface produces complex effects, and thermal radiation from surface bursts cannot be predicted as reliably as thermal radiation from air bursts. Values of effective thermal partition obtained from Figure 3-18 are estimated to be reliable within ±0.20 if the value is greater than 0.33. If the value that is read is less than 0.33, the lower limit of the expected range of values is 40 percent of the value that is read. The same tolerance is estimated for the effective thermal partition of the fireball as seen from above.

[redacted] *Related Material:* See paragraphs 3-1 through 3-3. See also Figure 3-1.

[redacted]

[redacted]

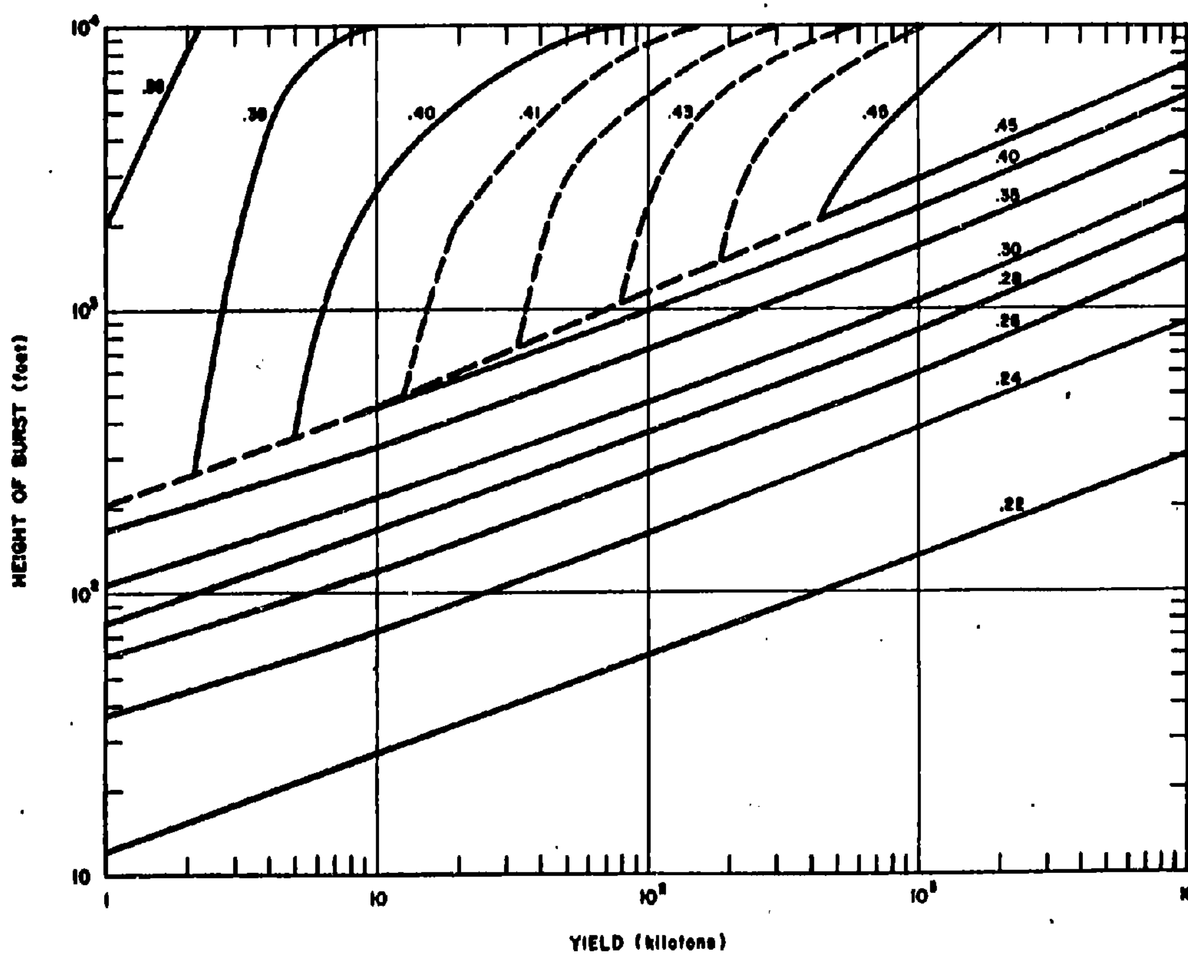

Figure 3-16. [redacted] Thermal Partition for Surface Bursts [redacted]

[redacted]

[redacted] THE THERMAL PULSE [redacted]

[redacted] Next in importance to the radiant energy incident on a target is the rate at which the energy is delivered. Dry leaves that receive a radiant exposure of 5 cal/cm^2 within a fraction of a second would ignite, but bright sunshine produces the same radiant exposure within about 3 minutes without producing ignition.

3-11 Thermal Power-Time Curve [redacted]

[redacted] Figure 3-19 shows the power-time curve for a 200 kt burst at an altitude of 5,000 feet. The shape is complex, with three peaks showing the results of competing processes (largely associated with the changing optical effects produced by the shock front) that alter the level of thermal radiation as the fireball evolves. Changes in burst altitude and weapon design can change the number and sizes of the peaks, therefore a complete, general description of thermal pulses is complex.

[redacted] If the curve of Figure 3-19 is normalized and plotted on linear graph paper it becomes much simpler, as shown in Figure 3-20. Also, since equal areas on the linear graph represent equal amounts of energy, the curve in Figure 3-20 is a more realistic indication of the amount of thermal damage that each portion of the pulse can produce. The first peak, which lasts only a fraction of a millisecond and which contains slightly over 0.1 percent of the energy of the pulse, cannot be seen. Even the second peak is so compressed by the linear time scale that most of it shows up as only a vertical line.

[redacted] When the features of the thermal pulse were first named, little more was known about the pulse than is shown in Figure 3-20; consequently, these two peaks and the valley were called *first maximum, light minimum,* and *second maximum.* Since the earlier features of the pulse produce negligible damage, many discussions ignore them; consequently, the names originally assigned to the later features still tend to be used even though these names are not strictly appropriate. In most of this chapter, the features shown in Figure 3-20 are called first maximum, principal minimum, and final maximum (i.e., the first maximum and first minimum shown in Figure 3-19 are ignored). The first maximum of low altitude bursts is sometimes called the shock exposure maximum, a name that suggests its physical origin. However, this name does not apply at all altitudes: above about 60,000 feet, the mechanism responsible for the first maximum changes.

3-12 Energy-Time Curve [redacted]

[redacted] The energy curve in Figure 3-20 shows the fraction of the thermal pulse energy that is radiated by a given normalized time. For example, it shows that 0.5 percent of the energy is radiated prior to principal minimum, that about 28 percent has been radiated by the time of final maximum, and that 15 percent is radiated at times later than are shown on the graph.

3-13 The Standard Thermal Pulse [redacted]

[redacted] Analysis of thermal radiation phenomena may be simplified by selecting the curves in Figure 3-20 as being representative of thermal pulses in general. Since changes in yield, altitude, and weapon design affect the shape of the pulse, use of such a standard is an approximation. Fortunately, this approximation is reasonably accurate for most bursts below 100,000 feet. The 200 kt burst at 5,000 feet was chosen as the basis for the standard thermal pulse for this manual because both yield and altitude have midrange values for typical thermal problems.

[redacted] Both of the curves in Figure 3-20 appear in dimensionless form. The normalizing parameters are t_{max}, the time of final maximum, and P_{max}, the radiated power at final maximum. Of these parameters, the more frequently calculated is t_{max}, which specifies the time scale of the entire thermal pulse. Values of t_{max} may be

[redacted]

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Figure 3-19. [redacted] Calculated Power-Time Curve for a 200 kiloton Burst at 5,000 feet [redacted]

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[redacted]

[redacted]

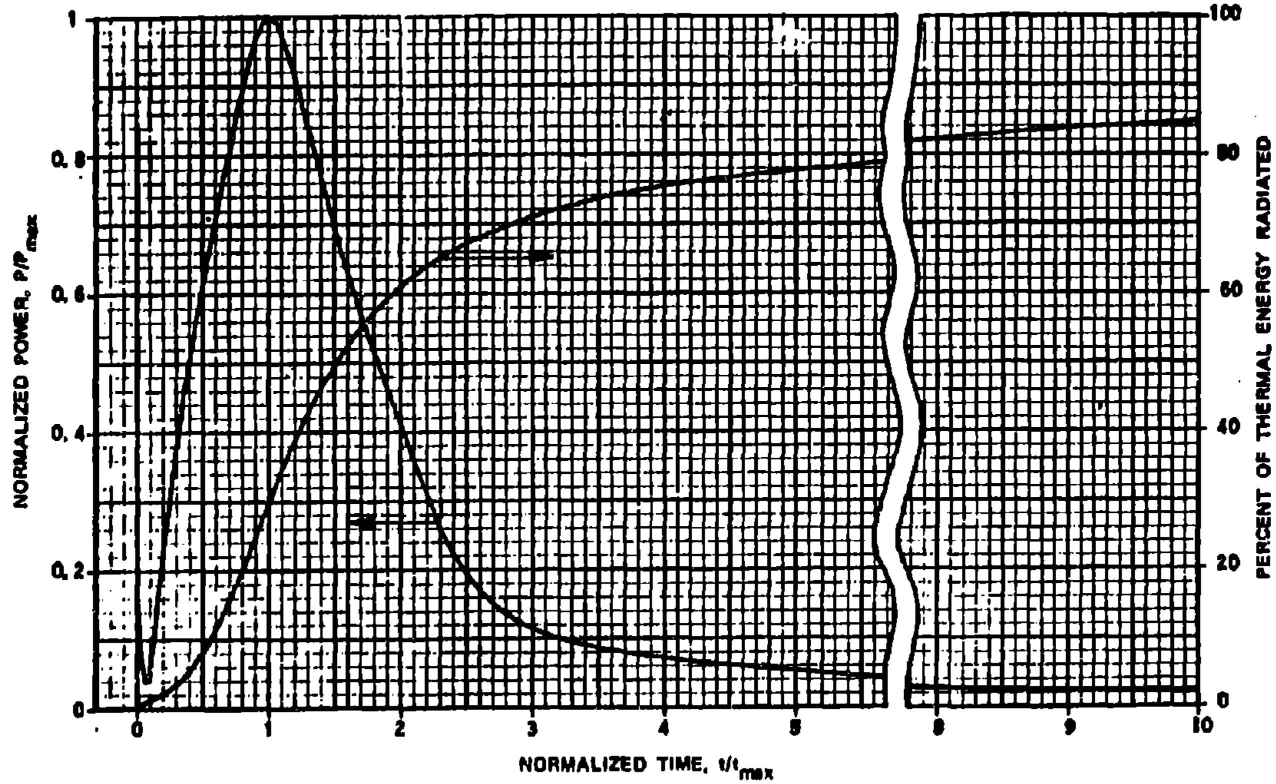

Figure 3-20. [redacted] Power-Time and Energy-Time Curves for a 200 kiloton Burst at 5,000 feet [redacted]

[redacted]

[redacted]

[redacted] obtained from Figure 3-21. Data for altitudes above 100,000 feet should not be used without consulting paragraph 3-19. Values of t_{max} also may be obtained from the equation

$$t_{max} = 0.043\ W^{0.43}\ (\rho/\rho_o)^{0.42}\ \text{sec},$$

where W is the yield in kilotons and ρ/ρ_o is the ratio of the air density at the altitude of interest to the air density at sea level. Equations for various thermal phenomena (including P_{max}) are summarized in paragraph 3-25. Table 3-4 shows values of ρ/ρ_o as a function of altitude.

[redacted]

Problem 3-6. Calculation of Time to Final Maximum

[redacted] Figure 3-21 shows the time to final maximum as a function of weapon yield and burst altitude. Values of t_{max} obtained from Figure 3-21 can be used to convert the normalized time scale in Figure 3-20 to actual time after burst.

[redacted] *Example* [redacted]

Given: A 25 kiloton explosion at an altitude of 50,000 feet.

Find: The time of the final maximum.

Solution: The value of t_{max} may be obtained directly by interpolation in Figure 3-21, or it may be calculated from the equation given in paragraph 3-13.

Answer: From Figure 3-21,

$$t_{max} \approx 0.078 \text{ sec.}$$

From the equation

$$t_{max} = 0.043 \ (W)^{0.43} \ (\rho/\rho_o)^{0.42}.$$

From Table 3-4, $\rho/\rho_o = 0.153$ at an altitude of 50,000 feet in a standard atmosphere. Therefore,

$$t_{max} = (0.043)(25)^{0.43} \ (0.153)^{0.42}$$

$$= 0.078 \text{ sec.}$$

[redacted] *Reliability:* Figure 3-21 was obtained from a combination of theoretical and experimental data. A description of the manner by which these numbers were derived is given in paragraph 3-25. Additional comments on the reliability are given in the subsection RELIABILITY OF THERMAL SOURCE DATA. Times given by this figure are estimated to be reliable within ±25 percent.

[redacted] *Related Material:* See paragraphs 3-11 through 3-13. See also paragraphs 3-24 and 3-25 and Table 3-4.

[redacted]

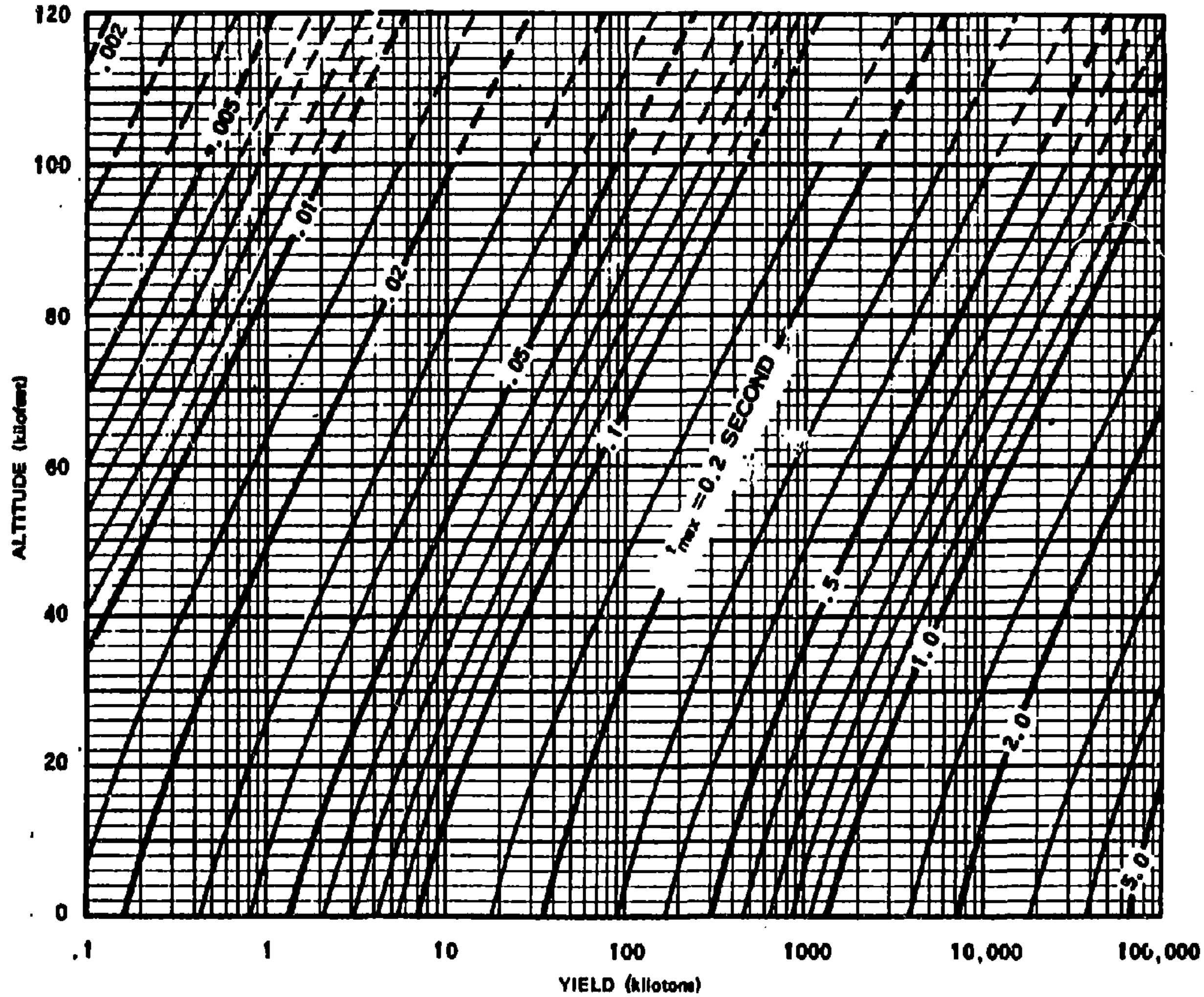

Figure 3-21. [redacted] Time of Final Maximum as a Function of Yield and Altitude [redacted]

[redacted]

3-14 Effect of Thermal Pulse Duration [redacted]

[redacted] For most target materials and a particular level of radiant exposure, there is a value of thermal pulse length that will produce maximum damage. If the pulse is too short, there will be too little time for the energy to penetrate the material of an opaque target. Consequently, the heat is confined to a thin surface layer. This layer will vaporize rapidly, and will carry the deposited energy away with it. Often, this vapor will be in the form of smoke, which will shield the target from later portions of the thermal pulse. If the pulse is too long, a thin target (e.g., paper) will dissipate the heat as it is received or a thick target will absorb the energy harmlessly in a thick layer of material.

[redacted] For the types of damage that receive the most attention – ignition of waste materials and skin burns – most nuclear bursts produce thermal pulses that are longer than the pulse that would produce maximum damage. Consequently, in almost every situation a short thermal pulse is more damaging than a long one. Short thermal pulses are produced by low yields and high burst altitudes.

[redacted] The reasoning that has been applied to different thermal pulses also can be applied to different portions of the same pulse. The first pulse is unimportant because of the small total energy that it contains. The final pulse radiates about 70 percent of the total pulse energy by 3 t_{max}, and this portion of the pulse produces most of the thermal damage. Another 15 percent of the pulse energy is radiated between 3 t_{max} and 10 t_{max}. This also contributes to thermal damage, but with reduced effectiveness because of the lower power level. The remaining 15 percent of the pulse is released after 10 t_{max} so slowly that it fails to add significantly to the total thermal damage.

3-15 Effect of Altitude on Pulse Shape [redacted]

[redacted] Although both yield and altitude affect the shape of the thermal pulse, the effect of altitude is the more severe. Below 100,000 feet, the changes are relatively minor. As illustrated in Figure 3-22, higher altitudes increase the relative width of the "first" pulse, which now contains sufficient energy to produce significant damage in some situations. The higher altitudes also decrease the depth of the principal minimum. The width of the final pulse on the dimensionless plot remains about the same, and the standard pulse shape is still a fair representation of the ability of the thermal pulse from a burst at 100,000 feet to produce damage. Thermal radiation damage to materials is discussed in Section III, Chapter 9, and thermal injuries are discussed in Section II, Chapter 10.

[redacted] Figure 3-23 shows a thermal pulse that was calculated for a 200 kt burst at an altitude of 40 km (131,000 feet). Between 100,000 feet and 131,000 feet, the pulse shape changes drastically. The principal minimum has disappeared, and even a logarithmic plot of this power-time curve would show only a single maximum. These differences in shape are caused by low air density (about 0.33 percent of sea level density) and the resulting weakness of shock wave effects. (As discussed in paragraph 3-25, the oscillations in the power-time curves of low altitude bursts depend strongly on the optical properties of the shock wave.)

3-16 The Effects of Thermal Pulse Specifications on Thermal Partition [redacted]

[redacted] The time at which the prompt thermal pulse ends must be specified in order to define the total energy of the thermal pulse. Among the logical choices are the following:

[redacted]

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Figure 3-22. [redacted] Power-Time Curve for a 200 kiloton Burst at 100,000 feet [redacted]

[redacted]

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Figure 3-23. [redacted] Power-Time Curve for a 200 kiloton Burst at 40 kilometers [redacted]

[redacted]

[redacted]

[redacted]

- Since the energy radiated after about 10 t_{max} produces little damage, 10 t_{max} is a logical cutoff time. This choice would have the effect of increasing the height of the energy curve so that it reaches 100 percent at 10 t_{max} in Figure 3-20.
- At times on the order of 20 or 30 t_{max}, fireball radiation becomes difficult to measure; therefore, the experimentally measured thermal pulse typically ends in this time range.

[redacted] Precedent may be found for either alternative. The definition selected in this chapter is approximately equivalent to the second choice listed above: the portion of the pulse after 10 t_{max} is assigned a value of 15 percent of the total pulse energy. This definition of the prompt thermal pulse agrees within a few percent with the thermal pulse as described in most reports on thermal pulse measurements and on thermal damage effects.

[redacted] Reports of theoretical calculations of the thermal pulse usually define the pulse energy in a way that corresponds roughly to the first alternative. The reason is a purely practical one: since calculation of the pulse beyond 10 t_{max} is neither accurate nor economical, the calculations usually are terminated at about 10 t_{max}. The reported energy content of the pulse is the energy contained in that portion of the pulse covered by the calculation. In reports describing these calculated results, a radiant exposure of 8.5 cal/cm^2 may imply the identical thermal pulse that is implied in this chapter by a radiant exposure of 10 cal/cm^2. Similarly, a thermal partition of 0.34 as reported, for example, in DASA 1589 (see bibliography) is reported in this chapter as approximately 0.40.

[redacted] The use of a standard thermal pulse introduces another problem. Since different thermal pulses have different shapes, the convenience of a standard pulse requires some sacrifice in accuracy. To minimize the effects of this loss in accuracy, the most damaging portion of the pulse is matched carefully but substantial errors are tolerated where power levels are low. Comparison of the pulse for 200 kt at 100,000 feet (Figure 3-22) with the standard pulse (Figure 3-20) shows that the two pulses are nearly equivalent near the time of final maximum but quite different at late times.

[redacted] To achieve this match, all parameters, including thermal partition, are chosen to give the correct power level and time scale at the time of final maximum. For the burst at 100,000 feet, the value of thermal partition so chosen is a few percent higher than a value based solely on total thermal energy. The standard pulse shape implies a level of late time radiation that the calculated thermal pulse for 100,000 feet fails to maintain. To match the high power portions of the calculated pulse to the standard pulse shape, thermal partition must be made artificially high.

[redacted] These matters of definition present no particular problem within this manual. Thermal pulses below 100,000 feet are specified so that the standard pulse shape, the assigned value of thermal energy, and the time of final maximum imply a pulse that provides a close match to the actual pulse in its ability to produce thermal damage. On the other hand, the user must keep these details in mind if he wishes to compare thermal data as given in this chapter with similar data from other sources.

[redacted] FIREBALL BRIGHTNESS [redacted]

[redacted] The surface of a nuclear fireball is many times brighter than the surface of the sun. The image of the fireball, brought to a focus on the retina of the eye, can produce burns and permanently damage the area covered by that image (see paragraph 10-20, Chapter 10). Fireball brightness is therefore one of the important parameters of the thermal source.

[redacted] A detailed study of eye damage also re-

[redacted]

[redacted] quires knowledge of the spectral distribution of thermal radiation and the transport properties of the air as a function of wavelength; however, the present discussion is limited to the most important and most easily used parameter, surface brightness. This quantity may be measured in terms of the total power per unit area radiated by the fireball. Convenient units are watts/cm². Brightness of the sun provides a useful standard for comparison. As viewed from outside of the atmosphere, the surface brightness of the sun is 6,350 watts/cm².

[redacted] For bursts below 100,000 feet, the approximate brightness of the fireball at final maximum is

$$B = \frac{2.7 \times 10^4}{W^{0.14} (\rho/\rho_o)^{0.42}} \text{ watts/cm}^2,$$

where W is yield in kilotons and ρ/ρ_o is the ratio of ambient air density at burst altitude to ambient air density at sea level. This equation gives a rough approximation of fireball brightness: more complete and accurate data for a particular yield and altitude may be found from the equation.

$$B = \frac{P}{4 \times 10^4 \pi R_f^2}$$

where P is power in watts radiated by the fireball and R_f is fireball radius in meters. Values of P and R_f as functions of time may be found for a wide range of yields and altitudes in "Theoretical Models for Nuclear Fireballs," DASA 1589 (see bibliography).

[redacted] Scattered light from a nuclear fireball can contribute to temporary flashblindness, but it is too diffuse to produce retinal burns. Consequently, the direct flux from the nuclear fireball is the only parameter of interest in the study of eye damage. Transmittance calculations are not appropriate, because they include scattered as well as direct flux.

[redacted] The direct flux received from a low altitude burst (burst height about 1/4 mile or less) is attenuated by the factor

$$T_d = e^{-2.9R/V}$$

where T_d is the transmission coefficient of the atmosphere for direct flux, R is the slant range, and V is visual range. For higher altitude bursts, the transmission coefficient is

$$T_d = e^{-\tau(h) \frac{R}{h} \frac{16}{V}}$$

where $\tau(h)$ is optical thickness of the model atmosphere with 16-mile visual range (Figure 3-2), and h is the height of burst.

[redacted] These equations give average attenuation for the entire fireball spectrum and underestimate the amount of infrared energy that the atmosphere can transmit. Since infrared contributes substantially to eye damage, exposure to fireball radiation may be somewhat more serious than the equations given above would indicate. Figures 10-6 through 10-10 provide estimates of safe separation distances for eye damage for various observer and burst altitudes.

[redacted] Cloud layers attenuate direct flux more than they attenuate radiant exposure. A cloud layer between the burst and the ground will produce the approximate attenuations shown in Table 3-3. The transmission coefficients shown in Table 3-3 are based on visible light, but they are expected to apply to the entire fireball spectrum within the limits to which a transmission coefficient can be matched to a particular sky condition.

[redacted] THE THERMAL PULSE FROM SPECIAL WEAPONS [redacted]

[redacted] As stated in paragraph 2-45, Chapter 2, weapons that have enhanced radiation out-

[redacted]

Table 3-3. [redacted] Attenuation of Direct Thermal Radiation by a Cloud or Haze Layer [redacted]

Type of Atmosphere	Description of Sky	Transmission Coefficient for Direct Flux
Very clear	Visual range is 25 miles or more. This condition is rare except at high altitude locations.	90.0%
Clear	Sky deep blue. Shadows are distinct and dark.	80.0%
Light haze	Sky white; dazzling near the sun. Shadows visible, gray.	3.0%
Medium haze	Sky bright grayish white. Can view sun without discomfort. Shadows are visible but faint.	0.1%
Heavy haze	Sky dull gray-white. The sun's disk is just visible. Shadows are barely discernible.	0.003%

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[redacted] puts, i.e., weapons that produce a large fraction of their output in the form of neutrons, gamma rays, or X-rays [redacted] will, in most cases, generate a weaker blast wave than a nominal weapon of the same yield. Similarly, the thermal pulse from such special weapons may be weaker than that from a nominal weapon. The explanation for the reduced thermal output is the same as the explanation for a weaker blast wave: neutrons, gamma rays, and high energy X-rays travel much farther through the atmosphere than the energy from a conventional weapon; therefore, a large portion of the weapon energy may be absorbed by air far from the burst. This air will not become sufficiently hot to contribute effectively to either the blast wave or to the thermal pulse.

[redacted] The terms "nominal weapon" and "conventional weapon" used in the preceding paragraph refer to a nuclear weapon that radiates 70 to 80 percent of its energy as X-rays [redacted] and retains nearly all of the remaining energy as thermal and kinetic energy of the weapon debris (see paragraph 4-4, Chapter 4). Such a source serves as a convenient starting point for calculations involving weapons with other characteristics. The procedures described in this subsection apply to burst altitudes of 100,000 feet and lower.

3-17 Effective Thermal Yield of Special Weapons [redacted]

[redacted] The modified thermal effects produced by weapons with enhanced outputs may be calculated in terms of an effective thermal yield. This is defined as the yield that a nominal warhead would have in order to radiate the same thermal energy as the special weapon. Effective thermal yield should not be interpreted to mean

[redacted]

[redacted] thermal energy radiated (a quantity sometimes assigned to the term "thermal yield"). Effective thermal yield means *the effective value of total yield* [redacted] *be used in thermal calculations.*

[redacted]The concept of effective thermal yield is an [redacted]simplification, and it cannot describe the performance of special weapons precisely. For example, the effective thermal yield calculated on the basis of time of final maximum will, in general, be slightly different from the effective thermal yield that gives the correct value of total thermal energy radiated. A still different effective thermal yield would predict the correct power at final maximum.

[redacted] In this subsection, effective thermal yield is the value that gives the correct value for therm: energy radiated, because, in most applications, this is the most important of the thermal parameters. Other parameters may be calculated by using this same value of effective thermal yield, but the calculation will be somewhat less accurate than if the procedure had been designed to calculate those parameters.

[redacted]Effective thermal yield is roughly the amount of energy that the nuclear source deposits within a sphere the size of the fireball at the time of the principal minimum. This radius is

$$R_{min} = \frac{95\ W^{0.36}}{(\rho/\rho_o)^{0.22}} \text{ feet}$$

$$= \frac{29\ W^{0.36}}{(\rho/\rho_o)^{0.22}} \text{ meters,}$$

where W is the weapon yield in kilotons, ρ is the ambient air density at the burst altitude, and ρ_o is the ambient density at sea level. Table 3-4 shows the ratio ρ/ρ_o as a function of altitude. Energy that is deposited beyond the radius R_{min} is assumed to make a negligible contribution to the energy radiated by the fireball.

Table 3-4. [redacted] Relative Air Density as a Function of Altitude [redacted]

Altitude (feet)	Relative Density,* ρ/ρ_o	Altitude (feet)	Relative Density,* ρ/ρ_o
0	1.000	80,000	0.0361
1,000	0.971	85,000	0.0284
2,000	0.943	90,000	0.0224
3,000	0.915	95,000	0.0176
4,000	0.888	100,000	0.0140
5,000	0.862	110,000	8.69-3†
10,000	0.739	120,000	5.43
15,000	0.629	130,000	3.45
20,000	0.533	140,000	2.22
25,000	0.449	150,000	1.45
30,000	0.375	160,000	9.77-4
35,000	0.311	170,000	6.69
40,000	0.247	180,000	4.65
45,000	0.194	190,000	3.22
50,000	0.153	200,000	2.22
55,000	0.121	210,000	1.54
60,000	0.0949	220,000	1.05
65,000	0.0747	230,000	7.05-5
70,000	0.0586	240,000	4.62
75,000	0.0459	250,000	2.60

[redacted] $\rho_o = 2.38 \times 10^{-3}$ slugs/ft^3 = 1.225 gm/cm^3.
† [redacted] 8.69-3 means 8.69×10^{-3}.

[redacted] Since the size of the fireball is determined by the thermal energy it contains, it would be logical to let W represent effective thermal yield rather than total weapon yield. To do this requires a trial-and-error approach. Effective yield is unknown until the equation given above has been solved and the energy deposited within R_{min} has been determined. In practice, the accuracy of this method for calculating effective thermal yield is sufficiently uncertain that this refinement is seldom justified. Unless [redacted] the effective thermal yield is less than half of the total yield, it is recommended that W be equated to total yield in the equation.

[redacted] To determine the amount of energy deposited within a radius R_{min} of the burst, the form of the energy emitted by the weapon must be determined. [redacted]

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[redacted] The steps in calculating the energy contained within R_{min} are:

1. Find the scaled radius

$$(\rho/\rho_o)\, R_{min} = 95\ W^{0.36}\ (\rho/\rho_o)^{0.78}\ \text{feet}$$

$$= 29\ W^{0.36}\ (\rho/\rho_o)^{0.78}\ \text{meters.}$$

This is the path length at sea level that passes through the same amount of air that a path of length R_{min} passes through at the burst altitude. Use of this scaled radius makes further scaling unnecessary.

2. Assume that 100 percent of the debris is contained within the radius.

3. [redacted]

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4. In a similar manner, find the amount of gamma ray energy that is deposited within R_{min} of the burst. The 1 MeV gamma photon curve in Figure 3-24 is approximately representative of the energy deposition properties of the gamma spectrum of a nuclear weapon.

5. [redacted]

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6. The components of energy deposited within R_{min} of the burst are added together to obtain the effective thermal yield [redacted]

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The calculation is then repeated on the basis of this new value of scaled radius.

[redacted] The effective thermal yield calculated by the procedures described above may be used to calculate other thermal parameters by the methods described in preceding paragraphs. For example, the effective thermal yield may be used as the weapon yield to calculate thermal partition as described in paragraph 3-1.

3-18 Thermal Pulse Shape from Special Weapons [redacted]

[redacted] The two properties that characterize special weapons (in the sense that the term is used in this chapter) are that the initial deposition of energy fills a large volume and that the density of the deposited energy drops gradually with distance from the point of burst when compared to nominal weapons. The early fireball of a conventional weapon rapidly develops a sharply defined edge, formed by the shock front. The sharply defined edge results in a very bright fireball; the diffuse fireball from an enhanced weapon is relatively dim, becoming bright only when the shock wave propagates through the incandescent region of the initial fireball and reaches cooler air.

[redacted]

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[redacted]

The thermal pulse assumes its conventional appearance at a time that depends on yield, altitude, and output properties of the nuclear device. [redacted]

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[redacted]

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[redacted]

[redacted]

Problem 3-7. Calculation of the Effective Thermal Yield of a Hot X-ray Warhead [redacted]

[redacted] Paragraph 3-17 outlines six steps to be used together with Figure 3-24 to determine the effective thermal yield of weapons with enhanced radiation outputs. The effective thermal yield thus obtained is used in place of the weapon yield to calculate the various thermal parameters as described in preceding paragraphs of this chapter.

[redacted] *Example* [redacted]

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[redacted] *Related Material:* See paragraphs 3-1 through 3-6, 3-17 and 3-18. See also paragraphs 4-4 through 4-8, Chapter 4.

[redacted]

[redacted]

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Figure 3-24. [redacted] Distribution of Deposited X-ray Energy in a Sea Level Atmosphere as a Function of Source Spectrum [redacted]

[redacted]

[redacted]

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[redacted] HIGH ALTITUDE THERMAL PHENOMENA [redacted]

[redacted] Both experimental and theoretical data are very limited, so the methods described are based on information that is sketchy at b[illegible]. An additional problem affects theoretical data: the approximations necessary to limit computer programs to a usable size become poorer at higher altitudes. Although many points of agreement exist between experimental data and the corresponding computer calculations, the confidence that can be placed on theoretical results is less at high altitudes than at low altitudes.

3-19 Thermal Partition [redacted]

[redacted] Two factors affect thermal partition at high altitudes. First, shock waves form much less readily in the thinner air; consequently the fireball is able to radiate thermal energy that would have been transformed to hydrodynamic energy of the blast wave at lower altitudes. Second, the thinner air allows energy from the nuclear source to travel much farther than is possible at sea level. Some of this energy travels so far from the source that it makes no contribution to the energy contained in the fireball.

[redacted] In general, the first of these factors becomes effective between about 100,000 and 140,000 feet, and, as a result, thermal efficiency rises. Above 140,000 feet, the second factor becomes the more important and efficiency drops.

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[redacted] As in the previous subsection on special weapons, this method requires that the X-ray output of the weapon be represented by the sum of several black body spectra. The energy density deposited at a given range may then be obtained from Figure 3-25a or 3-25b. Briefly, the scaling procedure is the following: the energy ΔE_2 = 2,500 cal/gm is scaled by the equation

$$\frac{\Delta E_2}{\Delta E_1} = \left(\frac{\rho}{\rho_o}\right)^2 \frac{W_2}{W_1}.$$

This equation is solved for ΔE_1, the value of energy to be read directly from Figure 3-25a or 3-25b. In this equation, ρ/ρ_o is the ratio of ambient air density at burst altitude to ambient

[redacted]

[redacted]

[redacted] density at sea level (Table 3-4), W_1 is a reference yield of 1 kt and W_2 is the energy, in kilotons, contained in a particular black body temperature component of the nuclear source.

[redacted] The scaled radius R_1 is read directly from the horizontal axis of Figure 3-25a or 3-25b. This radius is related to the actual radius R_2 by the scaling equation

$$\frac{R_1}{R_2} = \frac{\rho}{\rho_o}.$$

However, the rest of the problem does not require that R_2 be known; the calculation is based only on the scaled radius R_1. In general, R_1 is determined by more than a single spectral component; the way in which this calculation is performed is made clear in Problem 3-7.

[redacted] The method of treating debris, gamma, and neutron energy is identical to that described in paragraph 3-17.

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[redacted]

[redacted] The procedures described above apply to burst altitudes up to about 250,000 feet.

3-20 High Altitude Thermal Pulse Duration [redacted]

[redacted] Since the thermal pulse from a high altitude explosion rises to its maximum in an extremely short time and declines from that time (see Figure 3-23), pulse duration no longer can be specified in terms of the time to final maximum. A number that is useful in many applications is t_{70}, the time required for a pulse to deliver 70 percent of the total energy. At low altitudes,

$$t_{70} \approx 2.9\ t_{max}$$

and it follows that at high altitudes it might be possible to assign an effective time of final maximum such that

$$t_{max}\ \text{(effective)} = t_{70}/2.9.$$

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[redacted] Analyses of a limited number of computer calculations of high altitude burst phenomena show the following trends: below 80,000 feet, the equation holds within the scatter of the data; above 80,000 feet, the thermal pulse is delivered more rapidly than this equation predicts, until at 160,000 feet the pulse is only about a third as long as predicted by the equation, above 200,000 feet, the pulse approaches and, in one case, exceeds the predicted value. This behavior is shown in Figure 3-26.

[redacted]

[redacted]

Problem 3-8. Calculation of Thermal Energy Radiated from a High Altitude Explosion

[redacted] Figures 3-25a and 3-25b show the density of deposited energy from various energy sources as a function of range from a 1 kiloton explosion at sea level. These figures, together with the equations given in paragraph 3-19 provide the means to determine the thermal energy radiated by various yields at burst altitudes between about 120,000 feet and 250,000 feet. If the burst altitude is between 100 kft and 120 kft, thermal partition should be obtained by interpolation between the thermal partition obtained for 100 kft by the methods described in paragraph 3-1 and the thermal part[illegible]on determined by the methods illustrated b[illegible]ow. If the burst altitude is above 250,000 feet, refer to paragraph 3-21.

[redacted]

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Example 1 [redacted]

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[redacted]

Example 2 [redacted]

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[redacted] Related Material: See paragraphs 3-1 through 3-6 and 3-19 through 3-21. See also Table 3-4.

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Figure 3-26a. [redacted] Density of Deposited Energy from Various Energy Sources [redacted]

[redacted] [redacted]

[redacted]

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Figure 3-25b. [redacted] Density of Deposited Energy from Various Energy Sources [redacted]

[redacted] [redacted]

[redacted]

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Figure 3-28. [redacted] A Comparison of Calculated Effective Times of Final Maximum with Predictions from the Simplified Equation [redacted]

[redacted]

3-21 Bursts Above 250 Kilofeet [redacted]

[redacted] The calculations indicate that at heights of burst at or above about 290,000 feet the incandescent air heated by absorption of X-rays from the explosion is approximately at the same altitude, regardless of the actual height of burst. The heated region then reradiates at the longer wavelengths which could reach the ground. The reradiating region is in the form of a frustum of a cone, pointing upward, with a vertical thickness of approximately 45,000 feet and a mean altitude of 270,000. At this altitude, the radius of the frustum is roughly equal to the difference between the height of burst h and 270,000 feet, i.e., h - 270,000 feet. Consequently, as the burst altitude increases, the radius of the radiating region becomes greater but its thickness and altitude remain roughly constant. The shape of the region thus approaches a thick disk centered at about 270,000 feet altitude. The debris energy still is contained fairly locally until the height of burst reaches the debris stopping altitude of about 380,000 feet (see Table 8-1, Chapter 8), but the main effects of thermal energy delivered as a result of debris deposition at these altitudes are flashblindness or retinal burns (see Section II, Chapter 10). The total thermal energy emitted as a result of the debris deposition is masked by that energy emitted at lower altitudes as a result of X-ray deposition insofar as total energy that reaches the earth is concerned.

[redacted] About one-fourth of the X-ray energy from the explosion is absorbed in the low density air of the reradiating region, and only a small fraction, which decreases with the height of burst, is reradiated as secondary radiation. Consequently, only a few percent of the weapon energy is emitted as radiation capable of causing damage at the earth's surface. In fact, for bursts at altitudes exceeding about 330,000 feet the thermal radiation from a nuclear explosion even in the megaton range is essentially ineffective on the ground.

[redacted] If the horizontal distance d from ground zero, i.e., from the point on the ground immediately below the center of the disk-like region, to the position where the incident thermal energy is to be calculated is less than the height of burst, h, the source may be regarded as being located at the median radius of the disk in an altitude of 270,000 feet; this is indicated by the point S in Figure 3-27. Hence, for the target point X, the appropriate slant range is given by

$$R\ (\text{kilofeet}) = \left\{(270)^2 + [1/2\,(h - 270) - d]^2\right\}^{1/2},$$

with d and h in kilofeet. This expression holds even when d is greater than 1/2 (h - 270); although the quantity in the square brackets is then negative, the square is positive. The slant range, R_o, for ground zero is obtained by setting d equal to zero; thus,

$$R_o\ (\text{kilofeet}) = [(270)^2 + 1/2\,(h - 270)^2]^{1/2}.$$

If the distance d is greater than the height of burst, and equivalent point source is located at

[redacted]

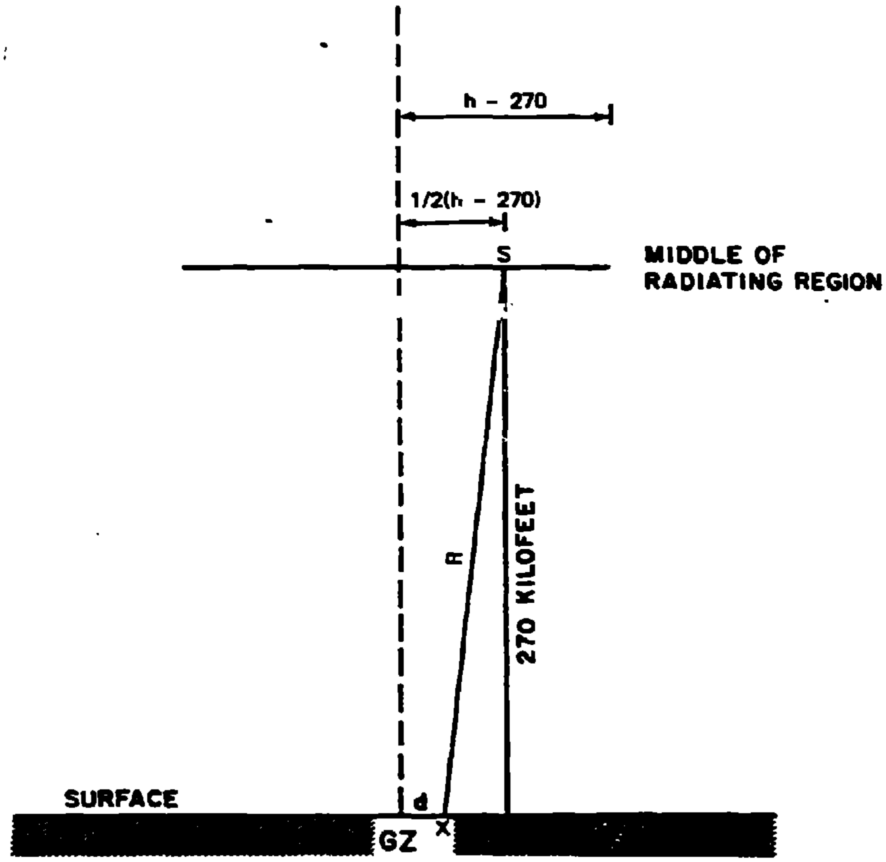

Figure 3-27. [redacted] Equivalent Point Source at Median Radius When Height of Burst Exceeds Distance of Target, X, from Ground Zero [redacted]

[redacted]

[redacted]

[redacted] the center of the radiating disk at 270,000 feet altitude; then

$$R \text{ (kilofeet)} = [(270)^2 + d^2]^{1/2}.$$

[redacted] The calculations assumed that 80 percent of the total yield is emitted as X-ray energy and that 25 percent of this energy is absorbed in the radiating disk region. Hence, 0.8 x 0.25 = 0.2 of the total yield is absorbed. For calculating the radiant exposure, the total yield W in the equations in paragraph 3-2 is consequently replaced by 0.2 W. Furthermore, the equivalent of the thermal partition is called the "thermal efficiency," ϵ, defined as the effective fraction of the absorbed energy that is reradiated. Hence, if R is in kilofeet, the equation for radiant exposure given in paragraph 3-2 becomes

$$Q = \frac{17.1\epsilon\ WT}{R^2}\ \text{cal/cm}^2.$$

The values of ϵ given in Figure 3-28 as a function of height of burst and yield were obtained by the theoretical calculations mentioned previously. The transmittance may be estimated from Figure 3-15, but no serious error would be involved by setting it equal to unity for the large burst heights involved. No attempt should be made to interpolate between values of radiant exposure obtained for a burst height of 250,000 feet by the method described in paragraph 3-19 and the values obtained for 290,000 feet by the method described in this paragraph. If values of radiant exposure from bursts between these altitudes are desired, it is recommended that the radiant exposure be calculated for each altitude (250,000 feet and 290,000 feet) and that the higher or lower value be taken as an estimate, depending on the direction of conservatism that is desired.

[redacted] RELIABILITY OF THERMAL SOURCE DATA [redacted]

[redacted] Most of the thermal radiation source data presented in this chapter were obtained from the series of computer runs reported in DASA 1589, "Theoretical Models for Nuclear Fireballs" (see bibliography). These data are not purely theoretical: development of the computer code included comparisons of calculated results with experimental data, and adjustments in the assumed weapon characteristics were made as a result of these comparisons.

[redacted] The advantages of computer data (provided that this choice can be justified) are:

(1) This method eliminates many random errors that are inherent in experimental data. These random errors include uncertainty in the exact value of nuclear yield, instrument errors, uncertainty in atmospheric transmittances, blurring of some results as a result of finite time resolution of certain instruments, and uncertainty in the methods for transforming measured data to the parameters required for thermal calculations.

(2) Computer calculations can generate a large amount of data for a wide range of yields and altitudes that are not available from experiments.

(3) Errors that appear in the code results are likely to be consistent; therefore, the code probably predicts the trends produced by changes in yield or altitude more accurately than it predicts the results of any individual burst.

[redacted] The disadvantage of using the code is that at best it gives only an approximation of the many processes that determine, directly or indirectly, the amount of thermal energy radiated. The method of accounting for spectral absorption lines is an example of the approximations that are required. A subroutine stores data for 151,528 different spectral lines, yet this is a small fraction of the number of lines that affect

[redacted]

[redacted]

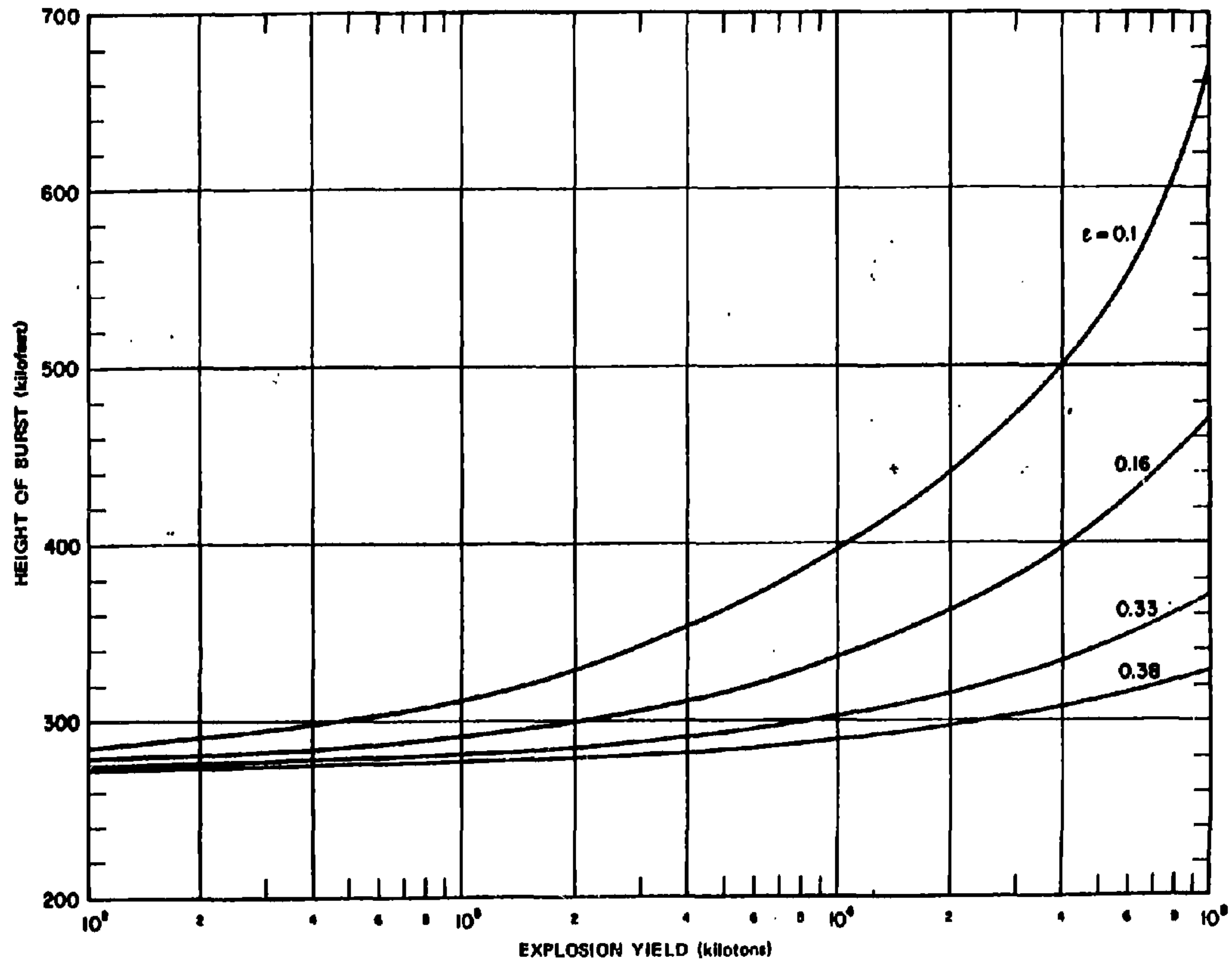

Figure 3-28. [redacted] Fraction of Absorbed X-ray Energy Reradiated [redacted]

[redacted]

[redacted]

[redacted] radiative transport within the fireball.

[redacted] Justification for using the code is the agreement between code results and measured data. The most striking areas of agreement are: (1) radius-time data, which are the most accurate experimental data, and (2) the ability of the code to reproduce intricate details of fireball evolution such as the fluctuations of the power-time curve (Figure 3-19) and the complex structure observed in high altitude fireballs.

[redacted] Unfortunately, the code-calculated parameters that are of more direct interest in this chapter (e.g., thermal partition) cannot be confirmed as accurately by experimental data. Since uncertainty in the experimental data generally is as great as the discrepancy between theory and experiment, the experimental data provide no clear indication of the reliability of the code results, e.g., the code reproduces observed fireball phenomena within the accuracy of most test measurements.

[redacted] This agreement has been obtained by comparisons of early code results with experimental data; however, changes in the code have never taken the form of arbitrary correction factors. Two examples illustrate the procedure used to correct the code.

[redacted] The code, as originally written, did not predict the correct level of radiation during the first maximum. Analysis of the radiative properties of the shock front revealed that a shock precursor (discussed in paragraph 3-25), a very thin layer of heated air ahead of the shock front, determines the radiative properties of the fireball during this interval. The fine structure of this precursor was lost by the approximate methods that were required to represent the shock front on the computer. A possible solution, much finer zoning in the region of the shock front, was rejected as uneconomical; however, a separate program to calculate shock-wave properties gave results that agree with the observed first maximum. This separate program was used to correct the radiation level that was calculated by the main computer program.

[redacted]

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[redacted] These illustrations show that the computed results are based on physical data. In a sense, experimental data are represented indirectly because they indicated the parts of the computer program that should be examined more closely. Nevertheless, agreement between code results and observations indicate that the physics of radiative transport and hydrodynamic motion is understood well enough that the computer program is an adequate representation of the fireball itself. Therefore, in this chapter these code results are tentatively accepted as the preferred source of data concerning the source of thermal radiation from nuclear fireballs.

[redacted] RELATION OF RADIANT EXPOSURE TO PEAK OVERPRESSURE [redacted]

[redacted] In many weapons effects problems, the first step is to determine which nuclear effect establishes the damage radius for a given burst. The series of figures in this subsection (Figure 3-29 through 3-56) show radiant exposure and peak overpressure as a function of height of burst and ground distance for 7 yields. The curves in these figures provide an aid in the determination of whether blast or thermal effects will be more important for specific situations. Four families of curves are presented for each yield. In each case the first two families of

[redacted]

[redacted] curves are for no atmospheric attenuation of the thermal radiation, i.e., the worst case thermal exposure, and the second two families of curves are for a visual range of 16 miles (a clear day). Table 3-5 shows a summary of the data presented in the figures.

[redacted] These curves reflect the data presented in preceding paragraphs of this chapter and the free field air blast data from Chapter 2 accurately for the yields and conditions shown on each figure; however, they do not provide the answers to all potential problems, e.g., only 7 yields are included, and no data are presented for visual ranges less than 16 miles. The curves are intended to be used as an aid in determining the relative importance of blast and thermal radiation. Their use can be extended beyond the particular values that are plotted. For instance, the value of radiant exposure obtained from the curves for no atmospheric attenuation may be converted to the value for any visual range by multiplying by the transmittance appropriate to the given conditions. Interpolation between yields will provide a first order, and frequently sufficient, estimate of the more important effect.

Table 3-5. [redacted] Summary of Blast-Thermal Curves [redacted]

Figure Number	Yield (kt)	Atmospheric Attenuation	Blast Values (psi)
3-29	0.01	None	10-50
3-30	0.01	None	1- 4
3-31	0.01	16 Mile Visual Range	10-50
3-32	0.01	16 Mile Visual Range	1- 4
3-33	0.1	None	10-50
3-34	0.1	None	1- 4
3-35	0.1	16 Mile Visual Range	10-50
3-36	0.1	16 Mile Visual Range	1- 4
3-37	1.0	None	10-50
3-38	1.0	None	1- 4
3-39	1.0	16 Mile Visual Range	10-50
3-40	1.0	16 Mile Visual Range	1- 4
3-41	10	None	10-50
3-42	10	None	1- 4
3-43	10	16 Mile Visual Range	10-50
3-44	10	16 Mile Visual Range	1- 4
3-45	100	None	10-50
3-46	100	None	1- 4
3-47	100	16 Mile Visual Range	10-50
3-48	100	16 Mile Visual Range	1- 4
3-49	1,000	None	10-50
3-50	1,000	None	1- 4
3-51	1,000	16 Mile Visual Range	10-50
3-52	1,000	16 Mile Visual Range	1- 4
3-53	10,000	None	10-50
3-54	10,000	None	1- 4
3-55	10,000	16 Mile Visual Range	10-50
3-56	10,000	16 Mile Visual Range	1- 4

[redacted]

[redacted]

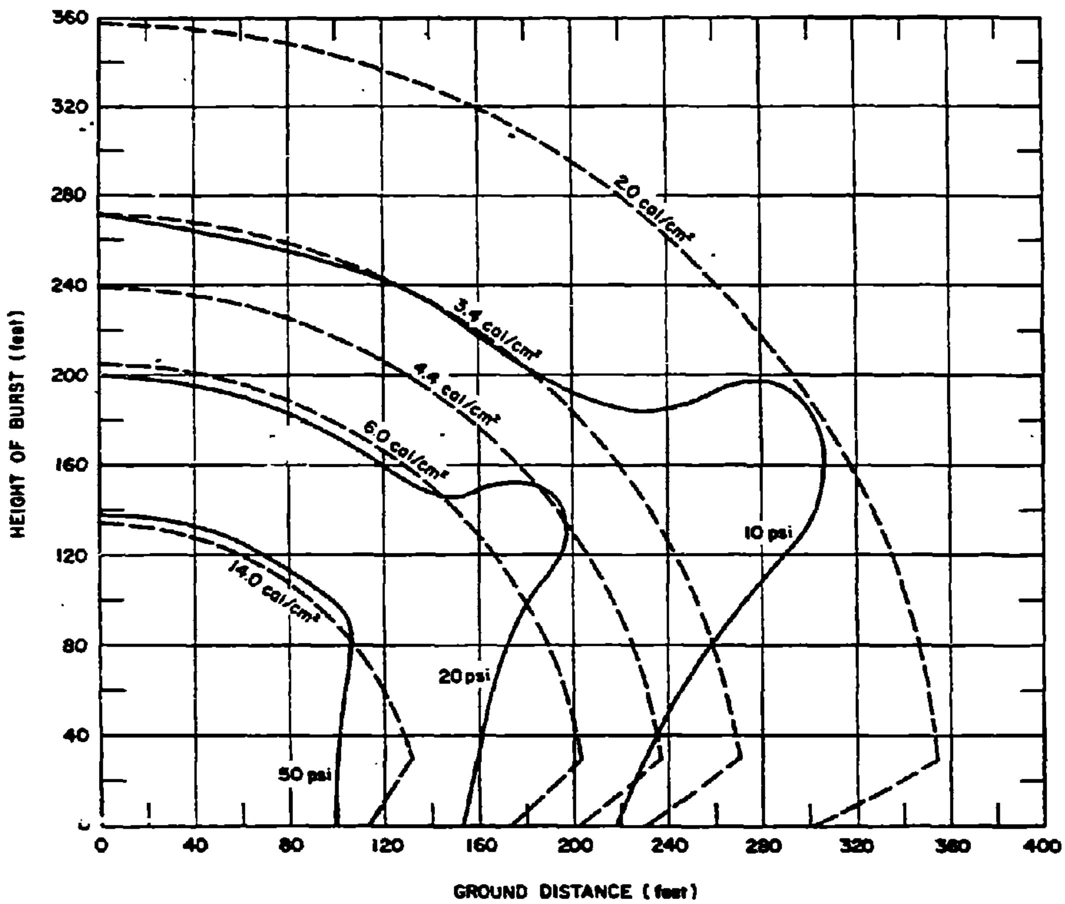

Figure 3-29. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 0.01 kilotons, No Atmospheric Attenuation, High Overpressure Region [redacted]

[redacted]

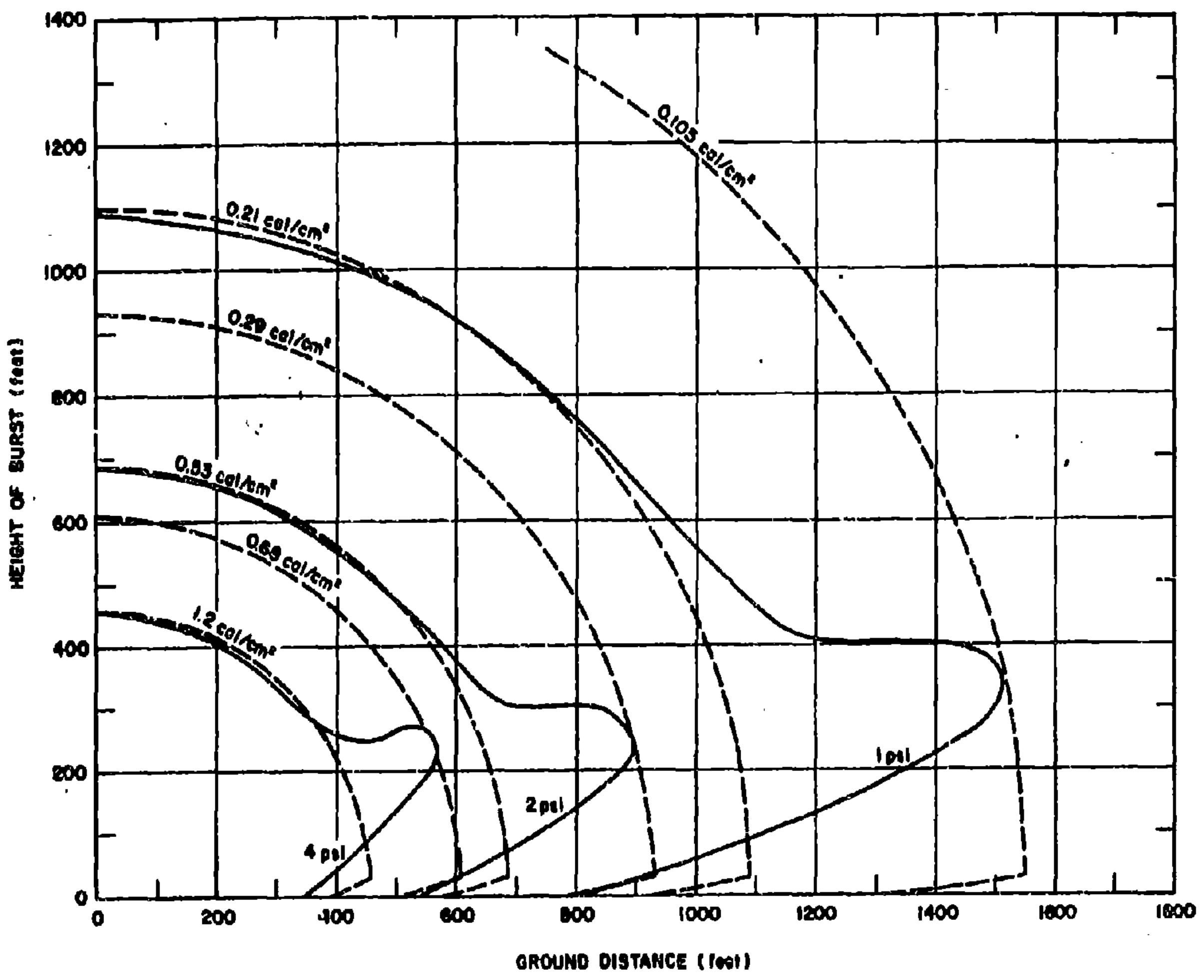

Figure 3-30. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 0.01 kilotons, No Atmospheric Attenuation, Low Overpressure Region [redacted]

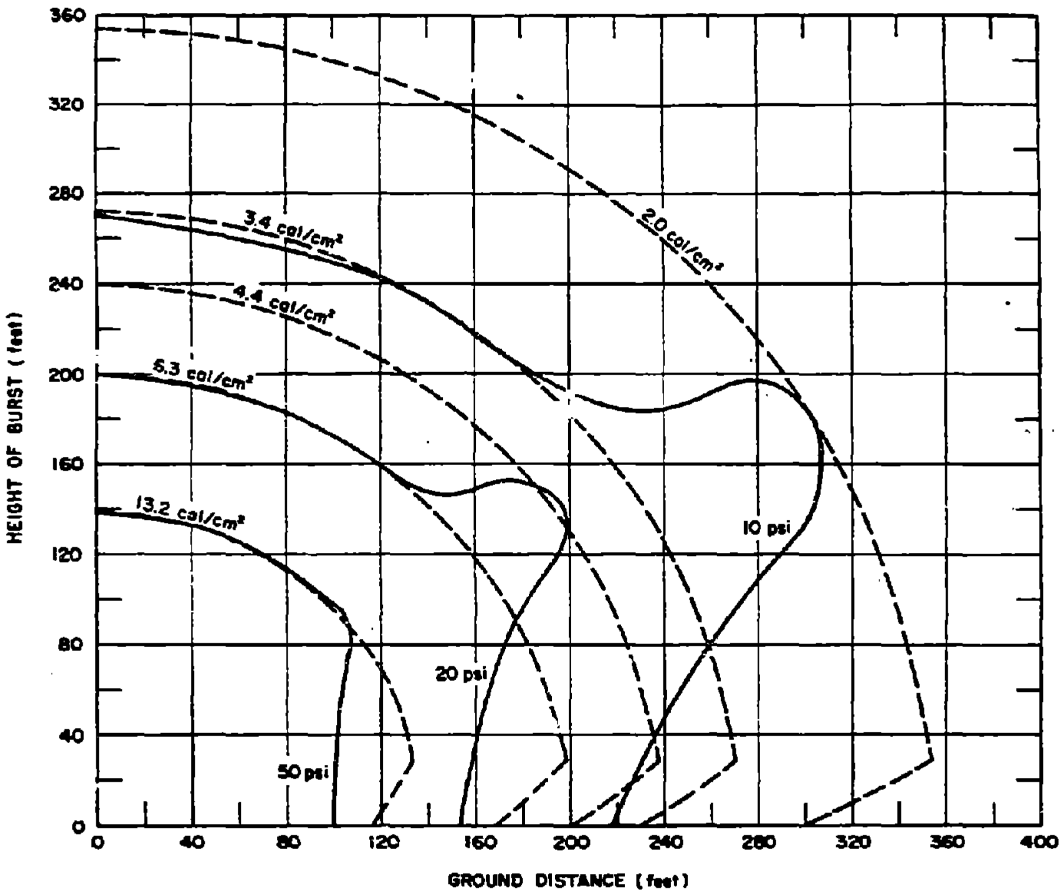

Figure 3-31. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 0.01 kilotons, 16 Mile Visual Range, High Overpressure Region: [redacted]

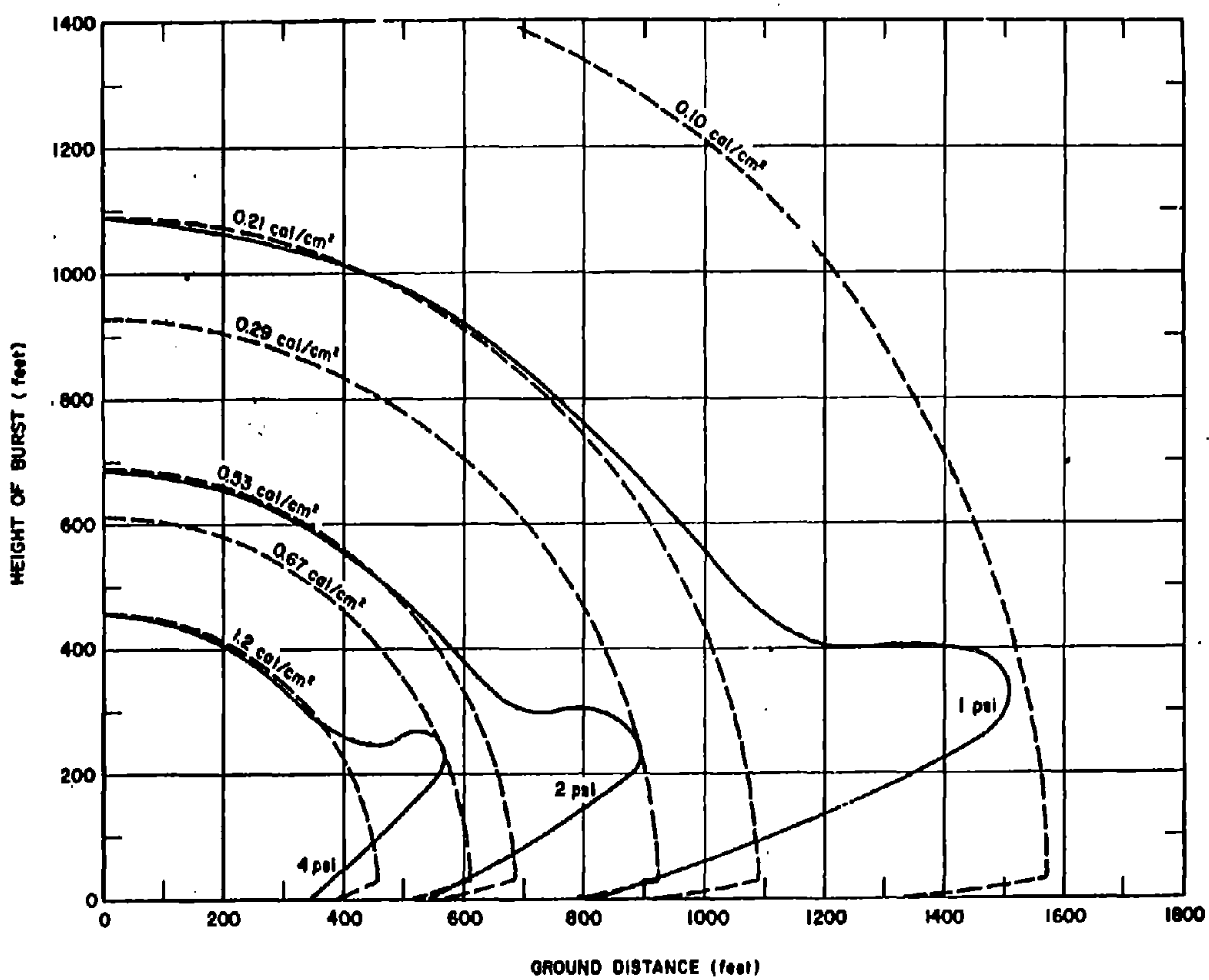

Figure 3-32. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, 0.01 kilotons, 10 Mile Visual Range, Low Overpressure Region [redacted]

[redacted]

[redacted]

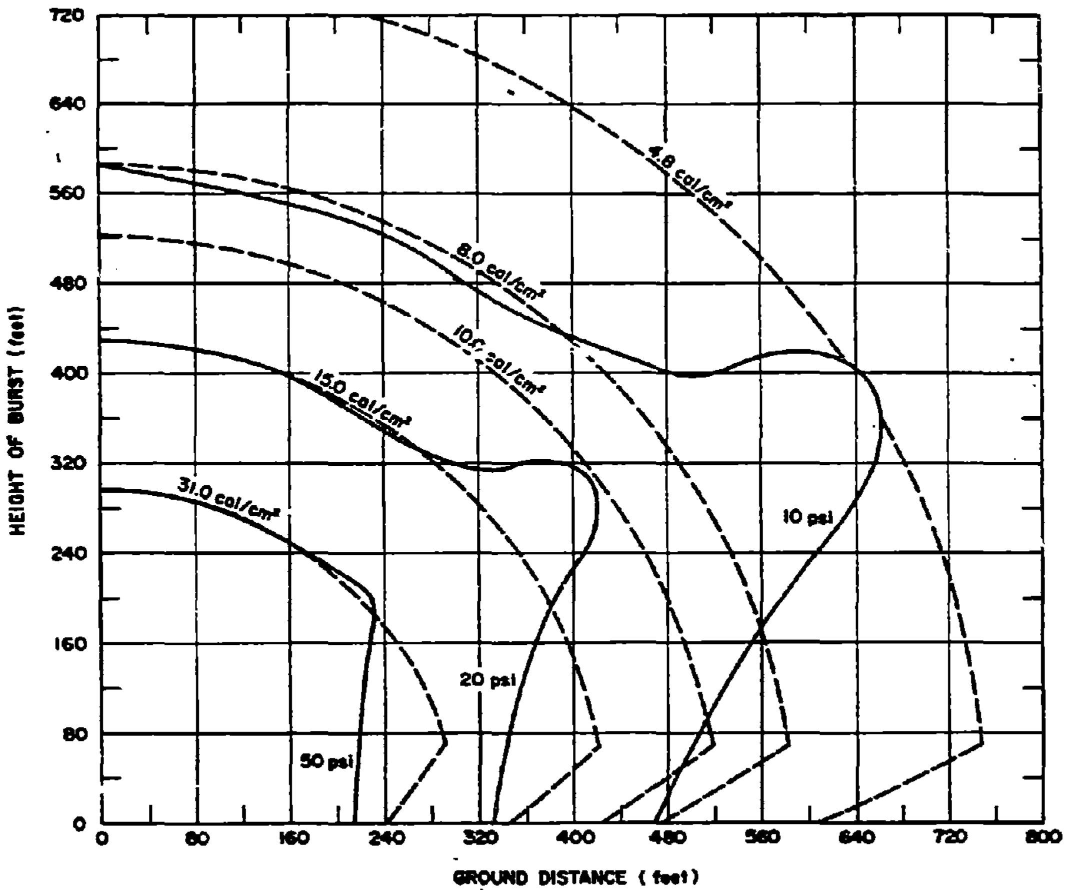

Figure 3-33. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 0.1 kilotons, No Atmospheric Attenuation, High Overpressure Region [redacted]

[redacted]

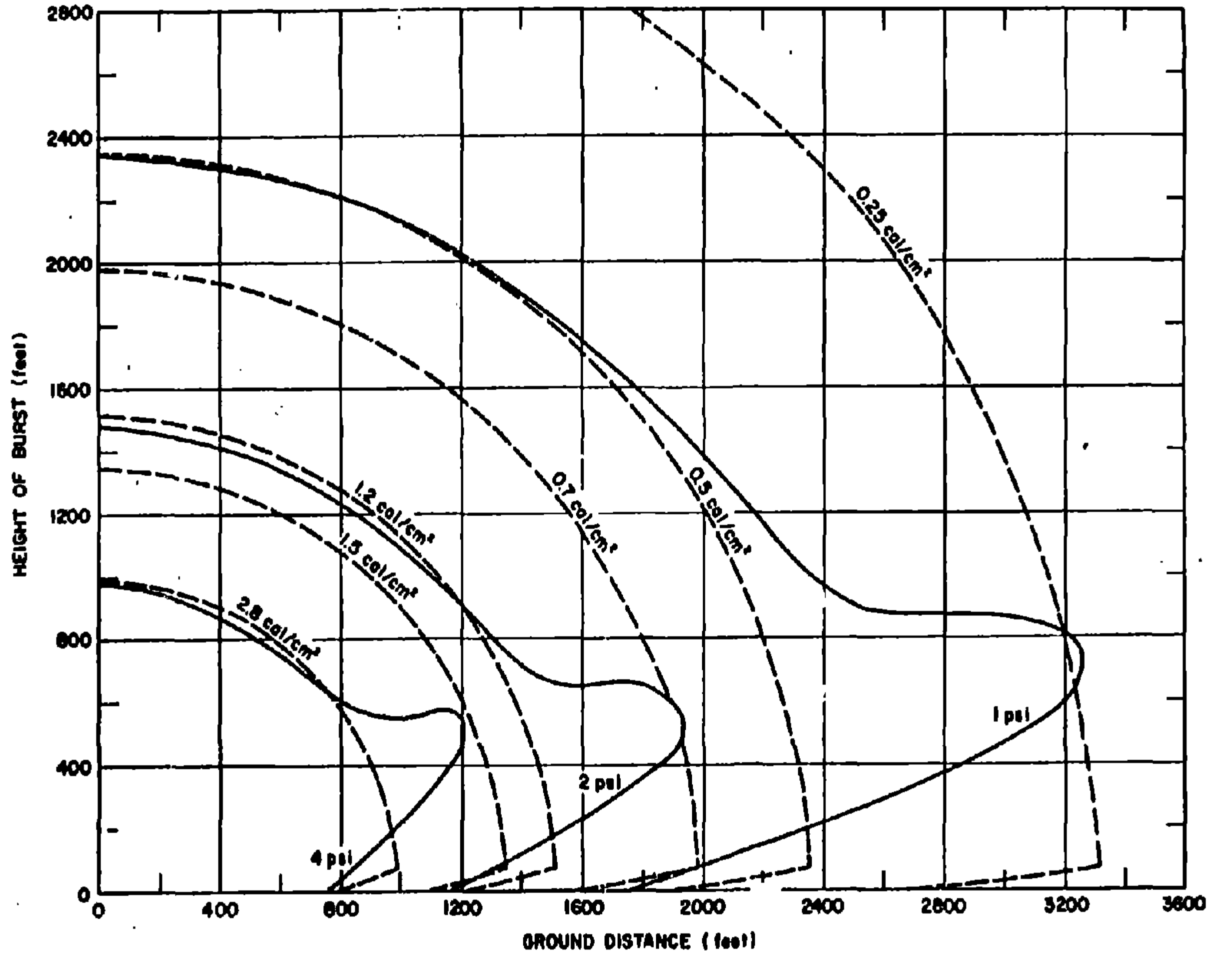

Figure 3-34. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 0.1 kilotons, No Atmospheric Attenuation, Low Overpressure Region [redacted]

[redacted]

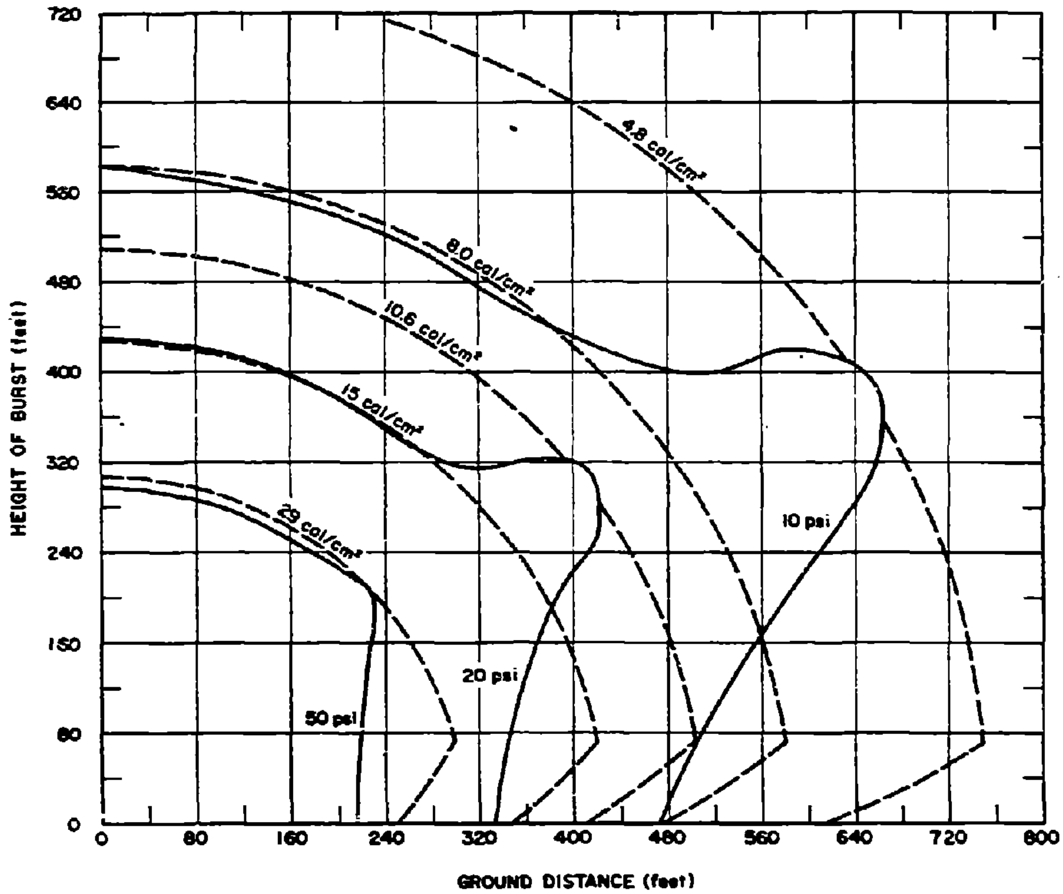

Figure 3-35. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 0.1 kilotons, 16 Mile Visual Range, High Overpressure Region [redacted]

[redacted]

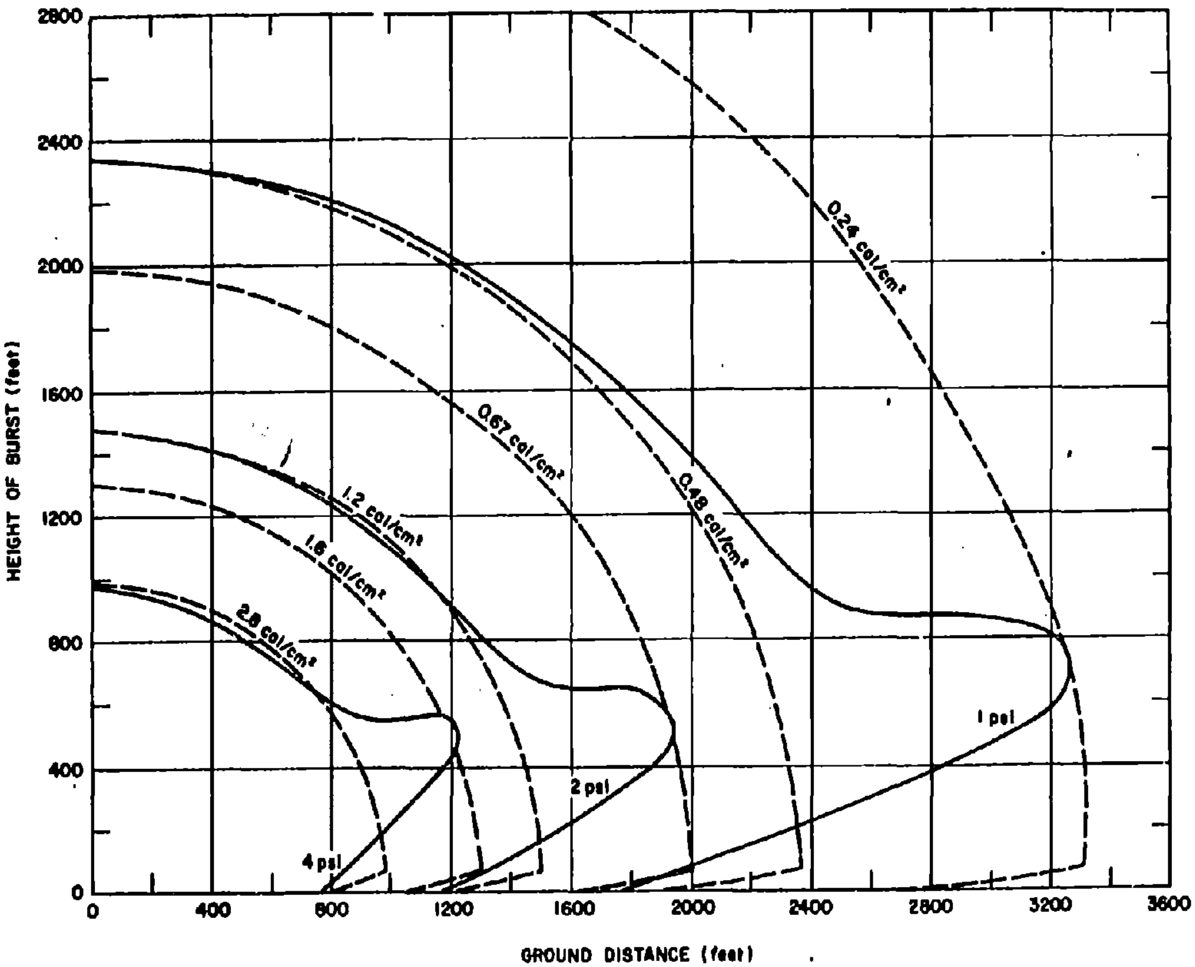

Figure 3-38. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 0.1 kilotons, 16 Mile Visual Range, Low Overpressure Region [redacted]

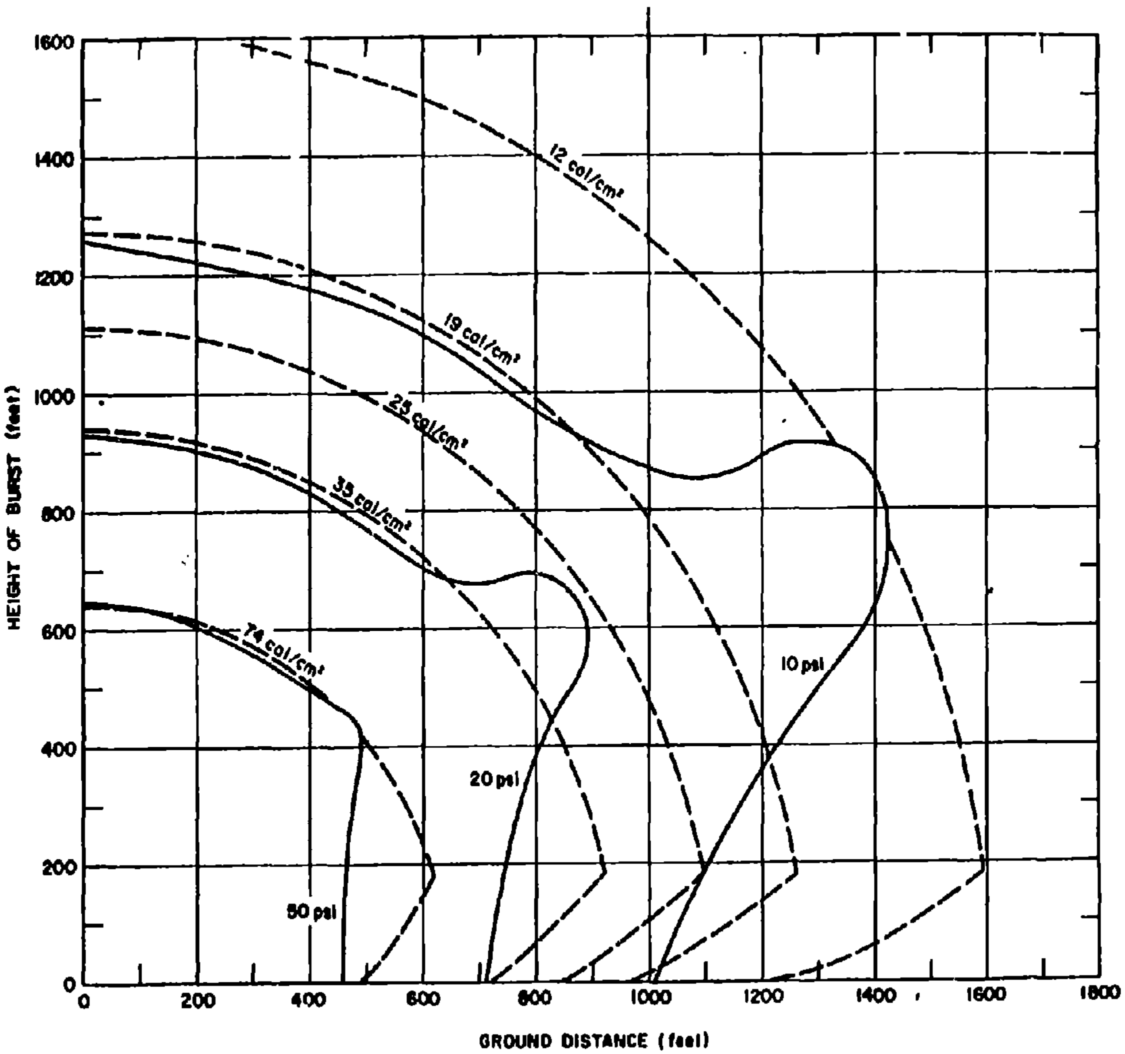

Figure 3-37. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 1 kiloton, No Atmospheric Attenuation, High Overpressure Region [redacted]

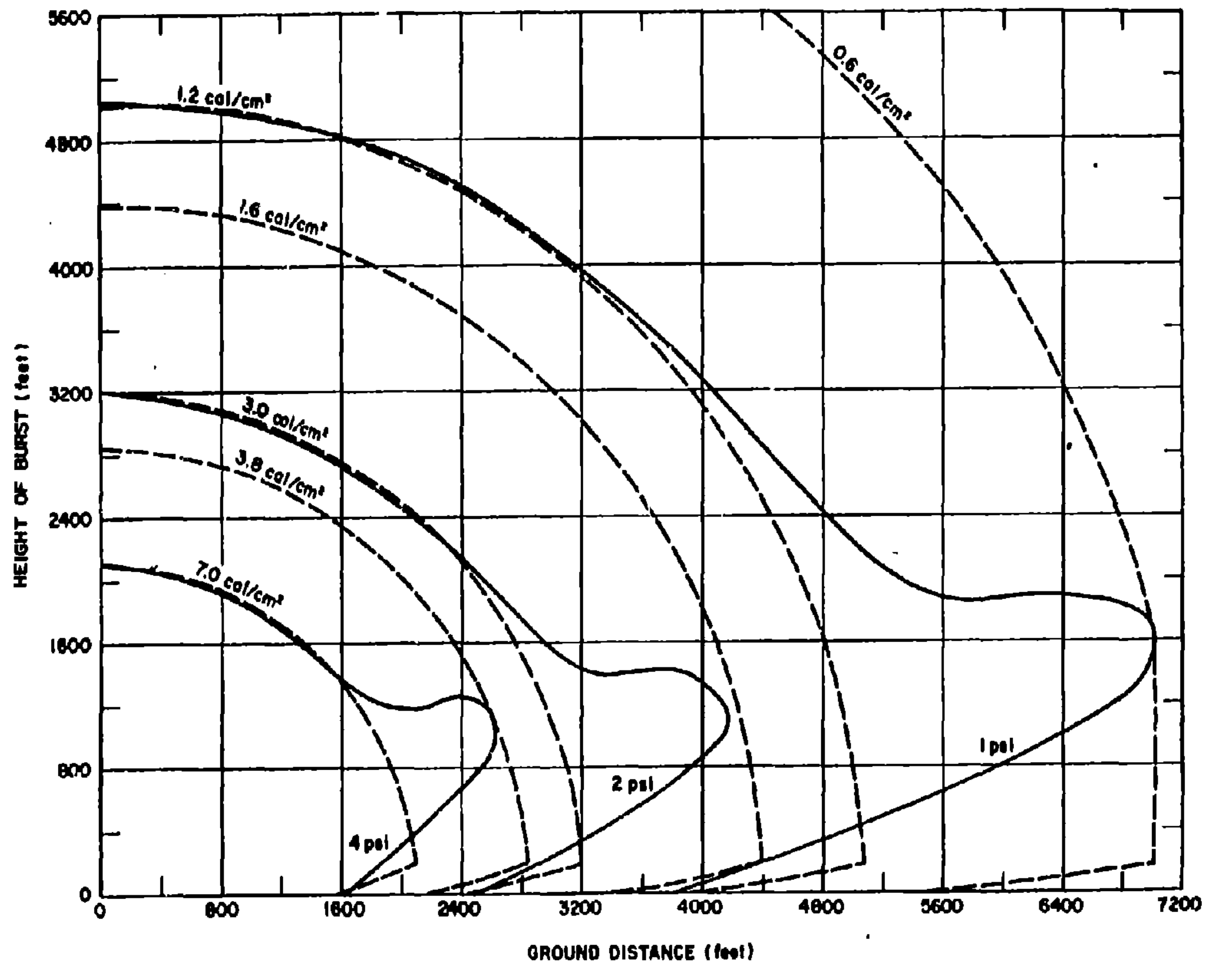

Figure 3-38. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 1 kiloton, No Atmospheric Attenuation, Low Overpressure Region [redacted]

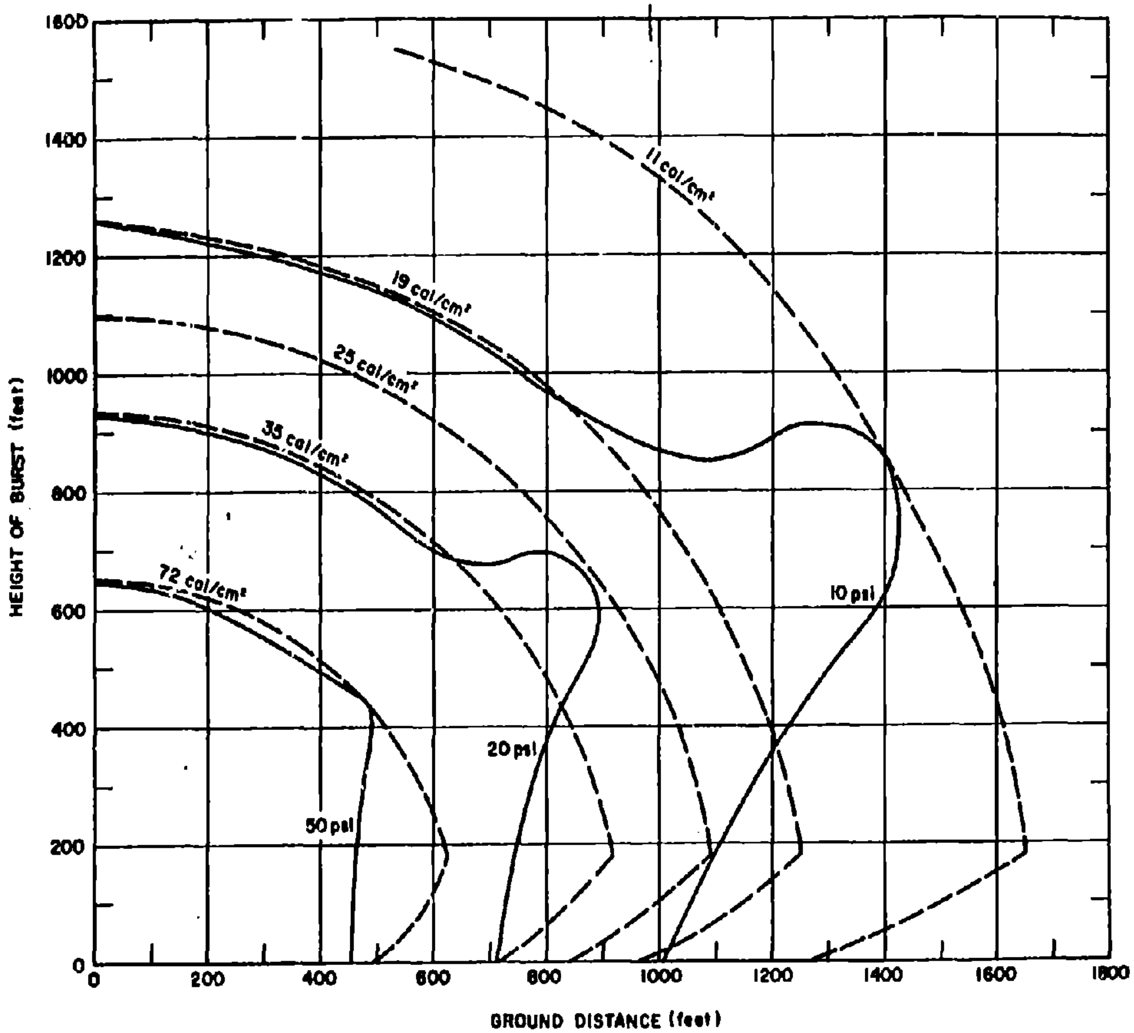

Figure 3-39. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 1 kiloton, 16 Mile Visual Range, High Overpressure Region [redacted]

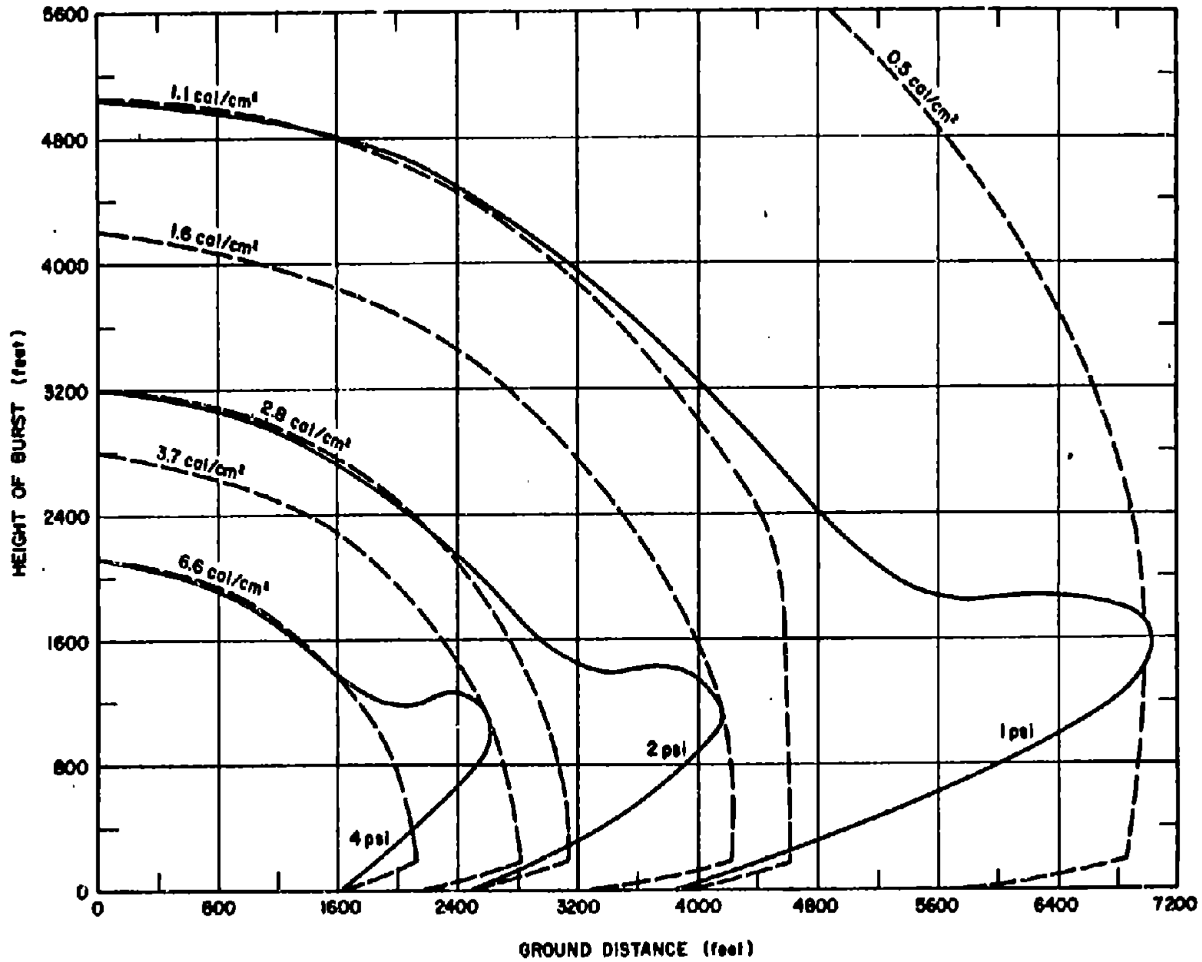

Figure 3-40. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 1 kiloton, 16 Mile Visual Range, Low Overpressure Region [redacted]

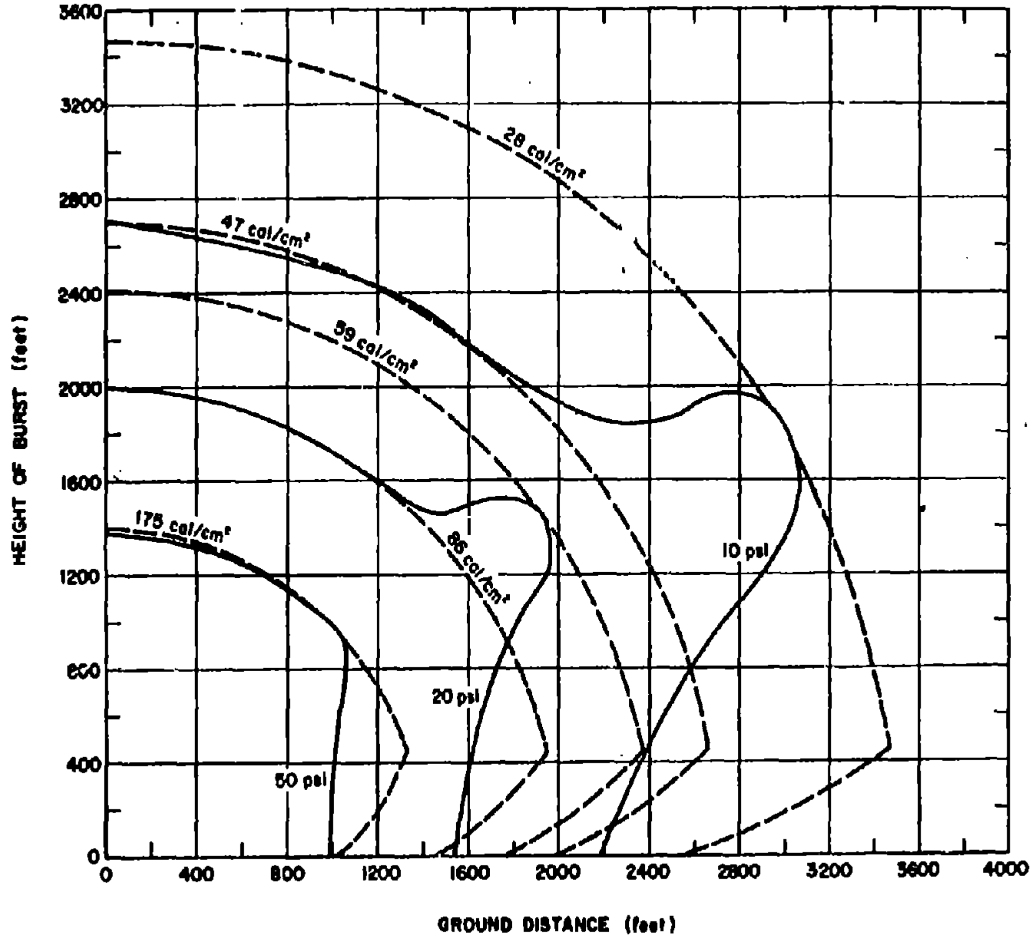

Figure 3-41. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 10 kilotons, No Atmospheric Attenuation, High Overpressure Region [redacted]

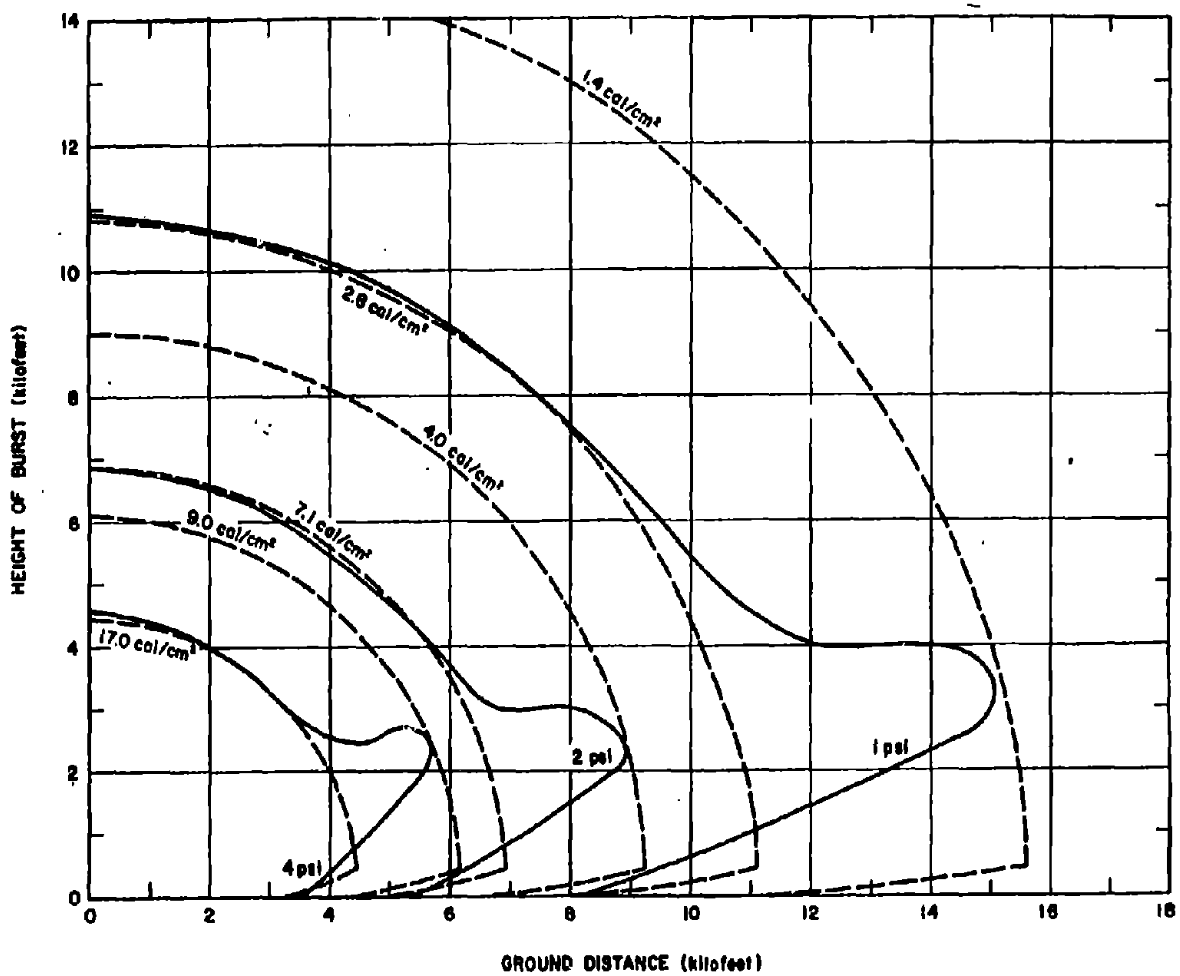

Figure 3-42. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 10 kilotons, No Atmospheric Attenuation, Low Overpressure Region [redacted]

[redacted]

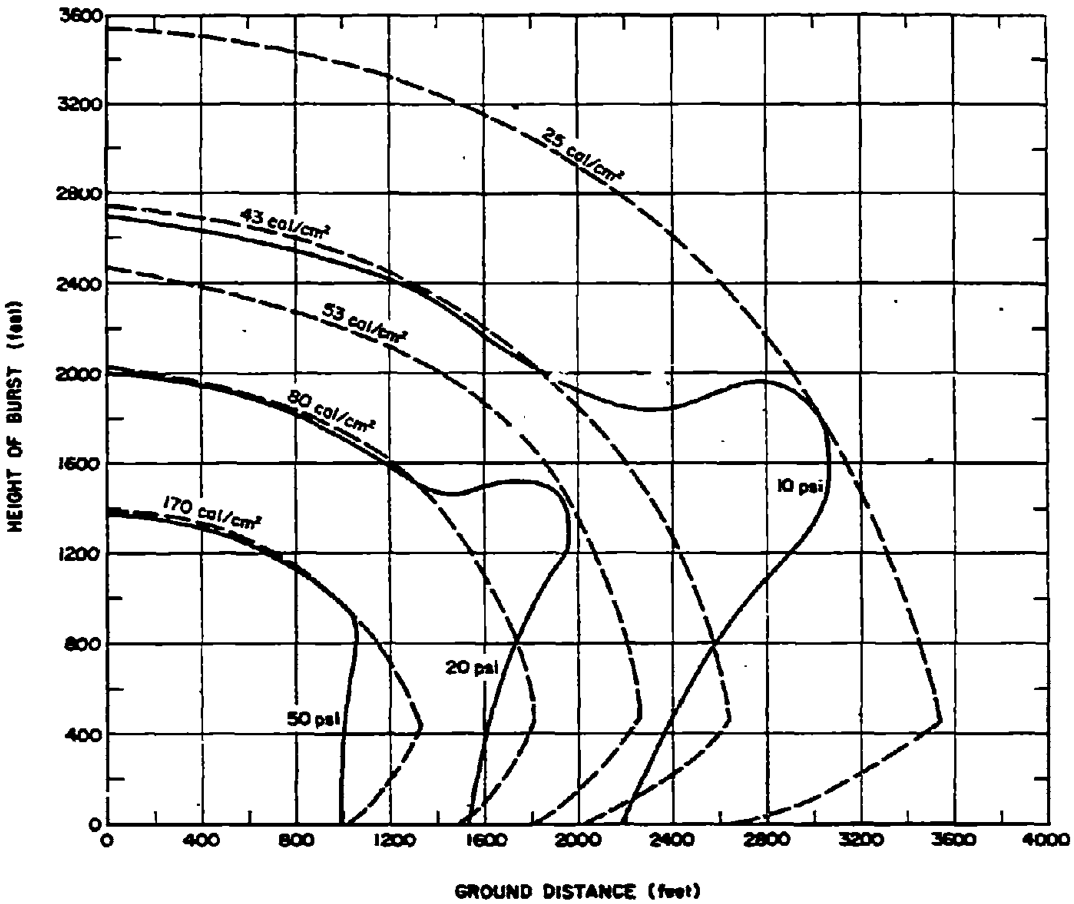

Figure 3-43. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 10 kilotons, 16 Mile Visual Range, High Overpressure Region [redacted]

[redacted]

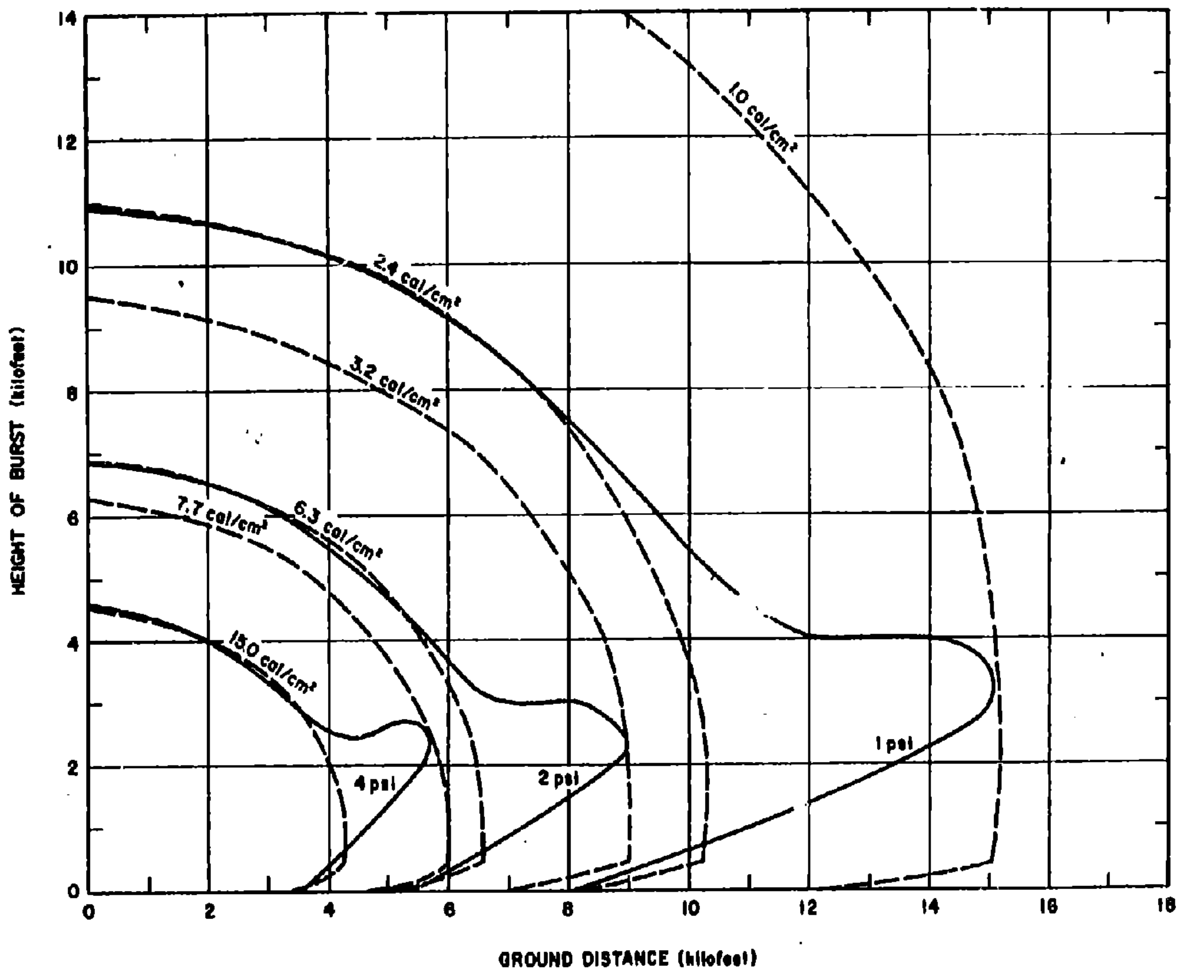

Figure 3-44. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 10 kilotons, 16 Mile Visual Range, Low Overpressure Region [redacted]

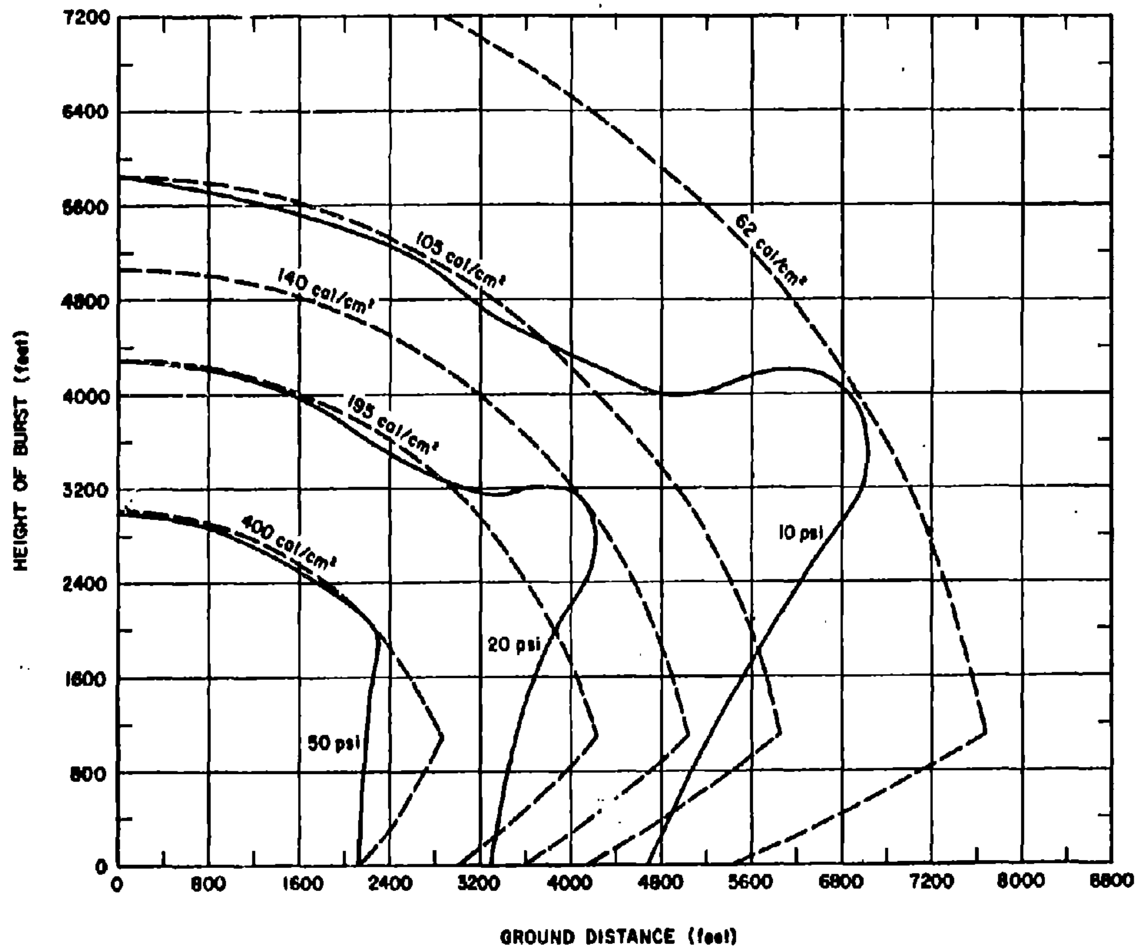

Figure 3-45. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 100 kilotons, No Atmospheric Attenuation, High Overpressure Region [redacted]

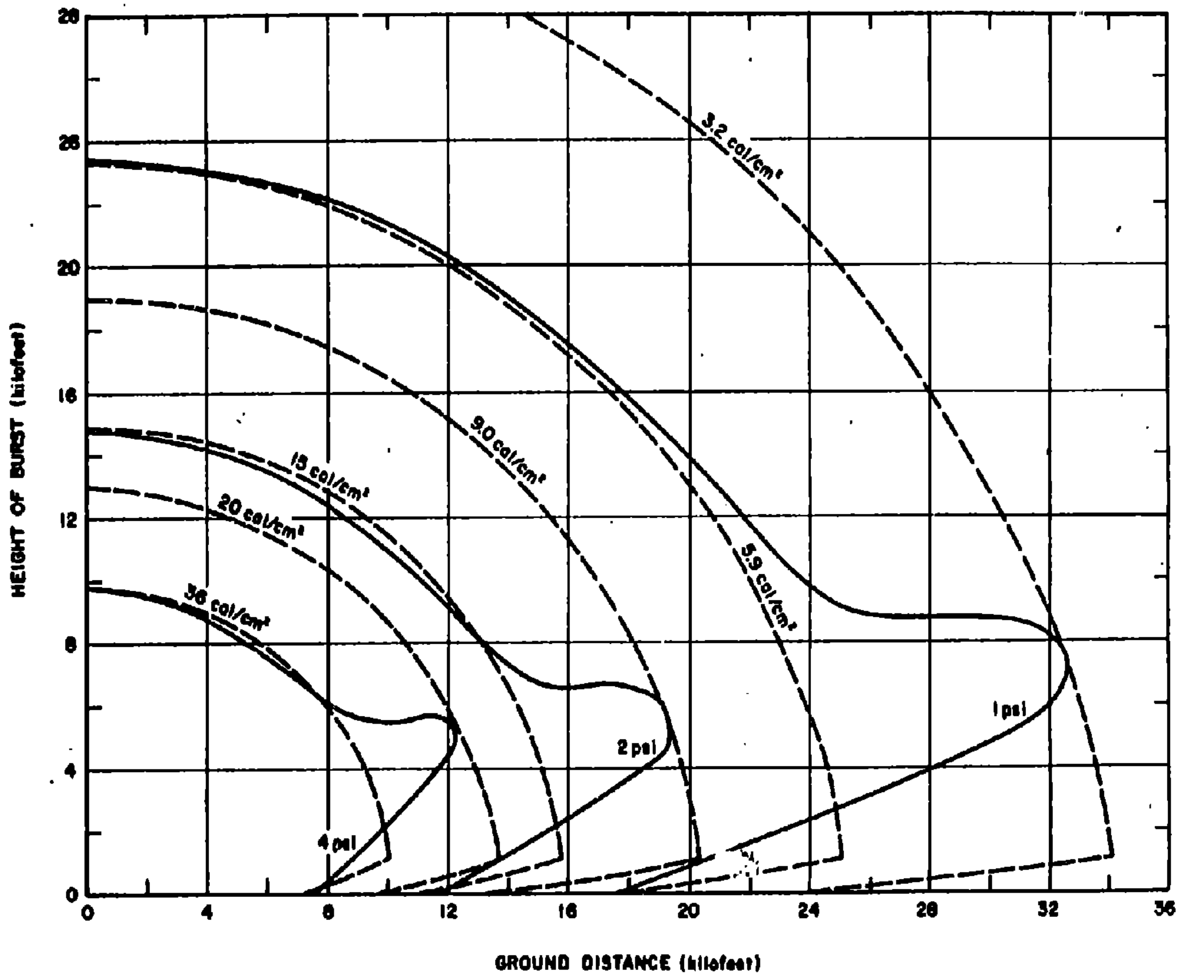

Figure 3-46. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 100 kilotons, No Atmospheric Attenuation, Low Overpressure Region [redacted]

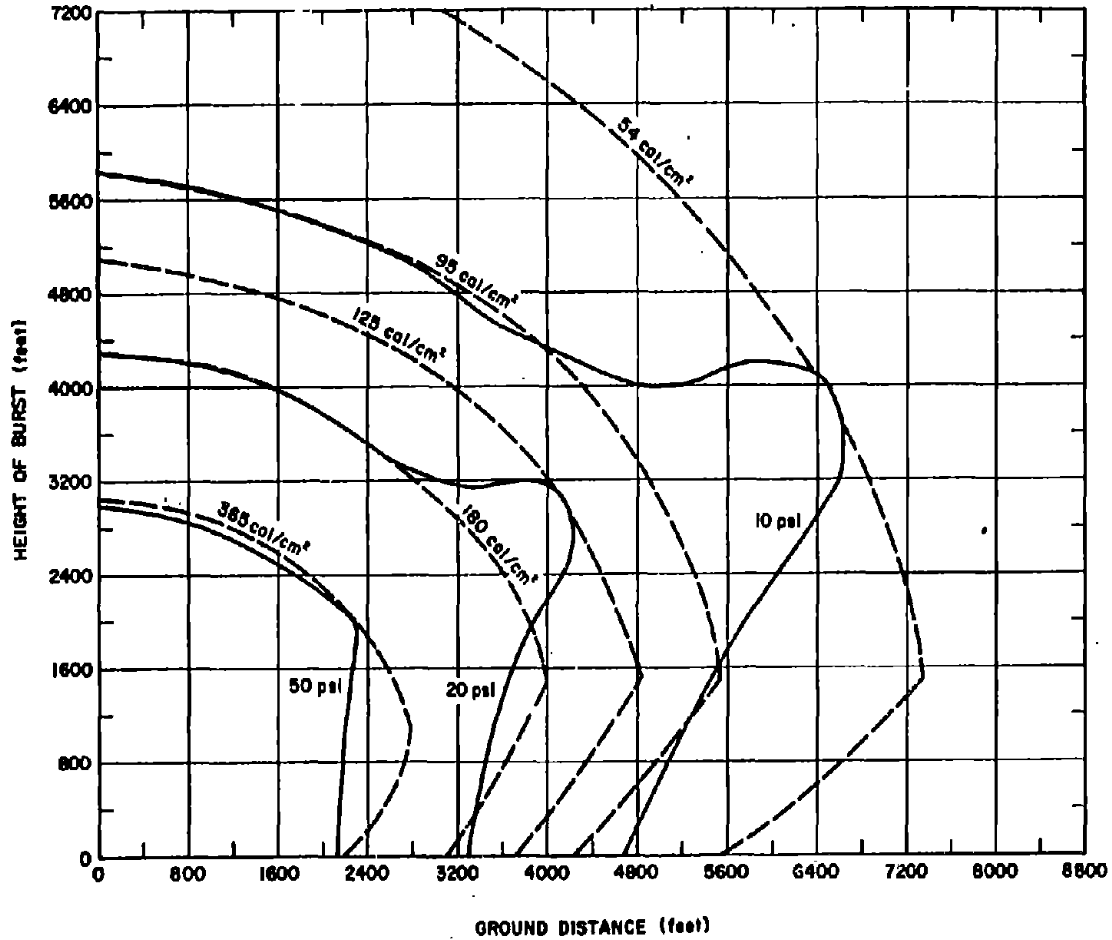

Figure 3-47. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 100 kilotons, 16 Mile Visual Range, High Overpressure Region [redacted]

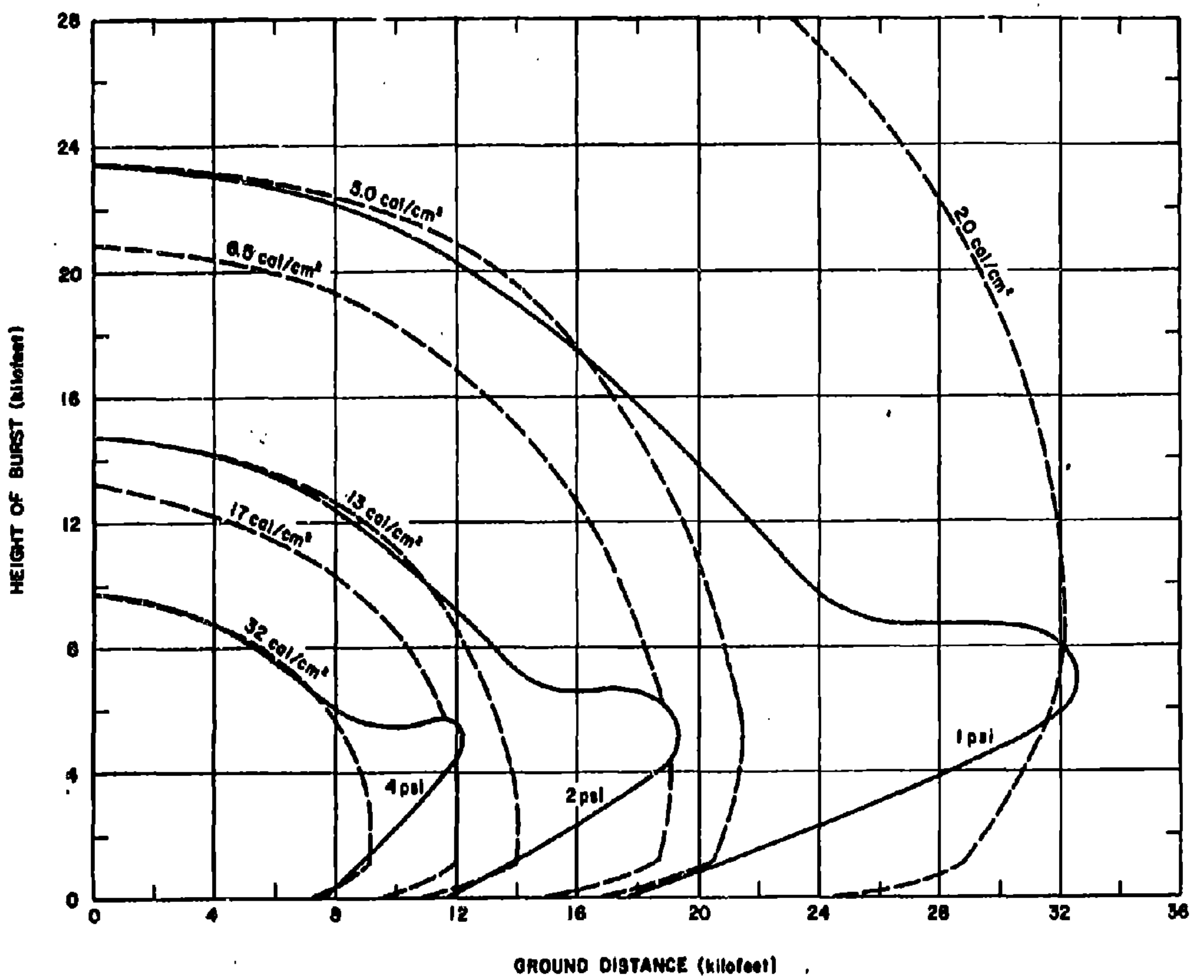

Figure 3-48. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 100 kilotons, 16 Mile Visual Range, Low Overpressure Region [redacted]

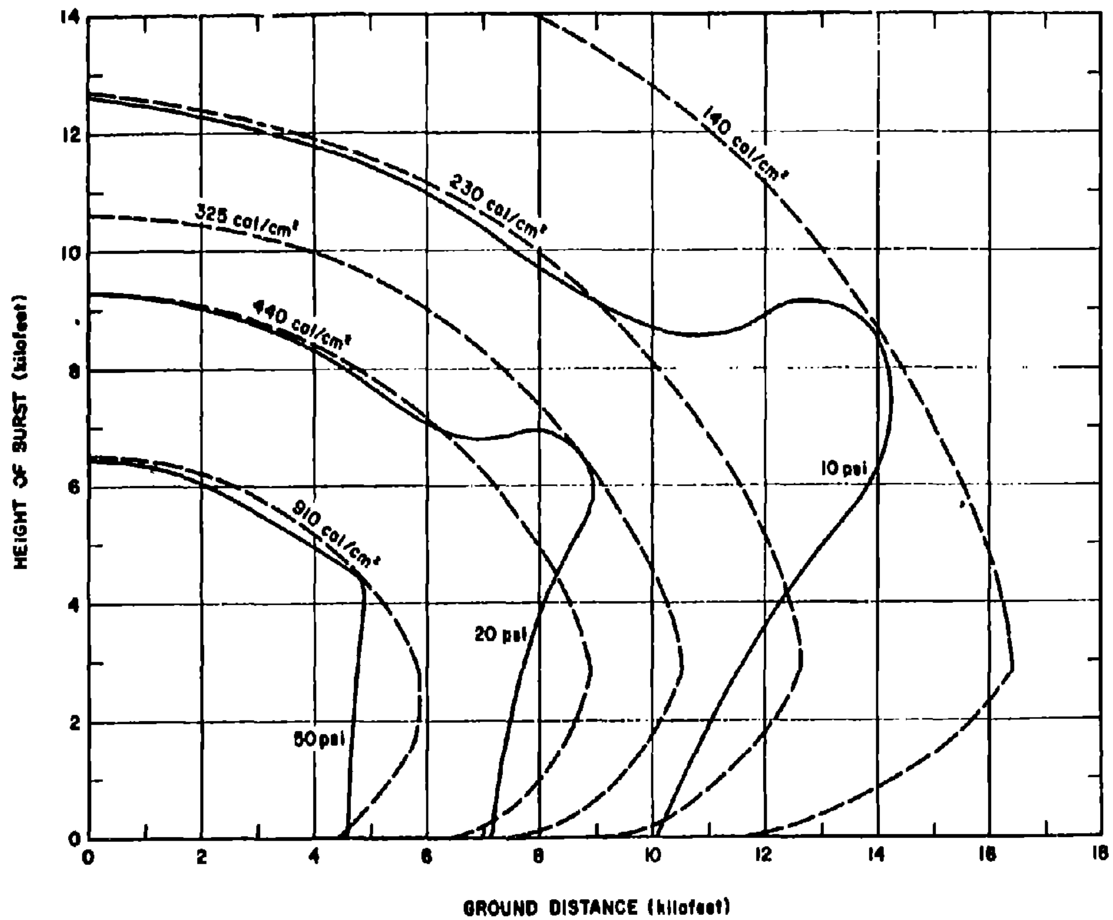

Figure 3-49. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 1 megaton, No Atmospheric Attenuation, High Overpressure Region [redacted]

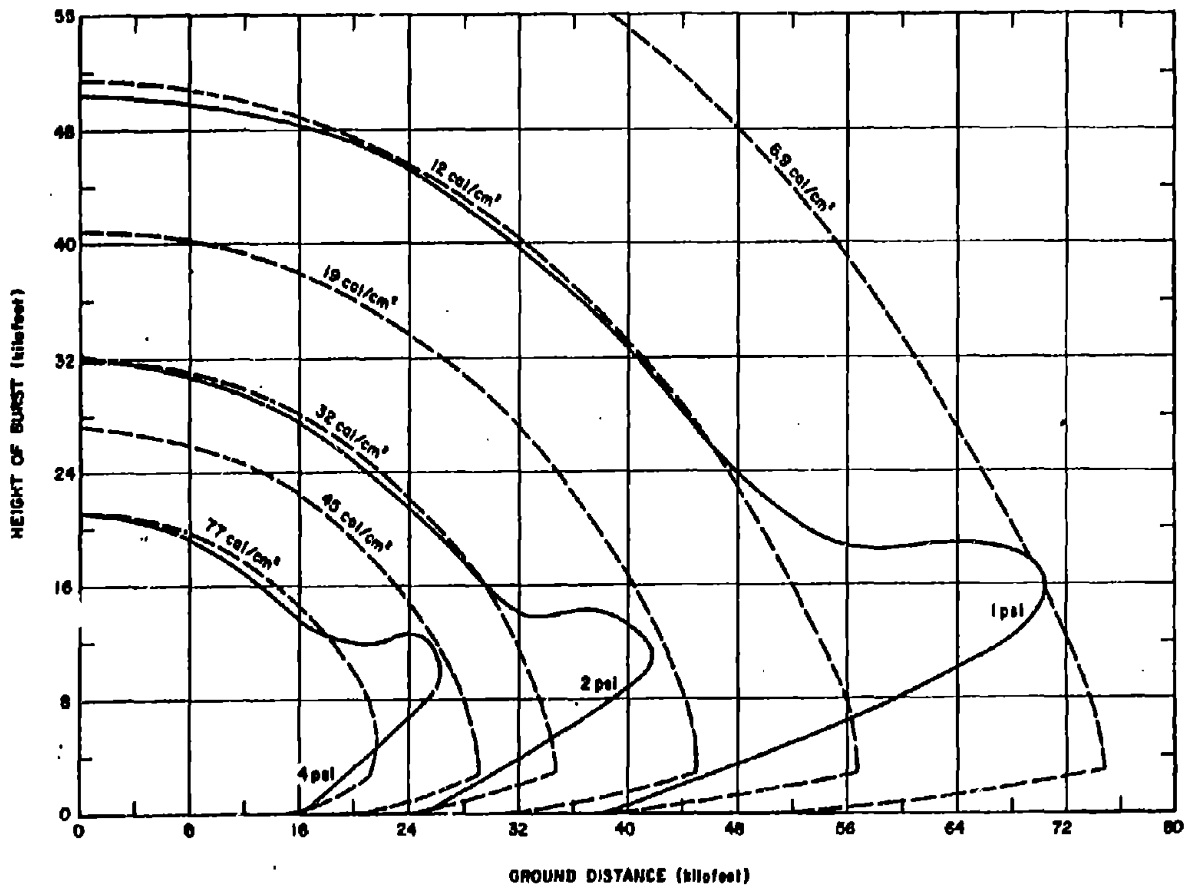

Figure 3-50. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 1 megaton, No Atmospheric Attenuation, Low Overpressure Region [redacted]

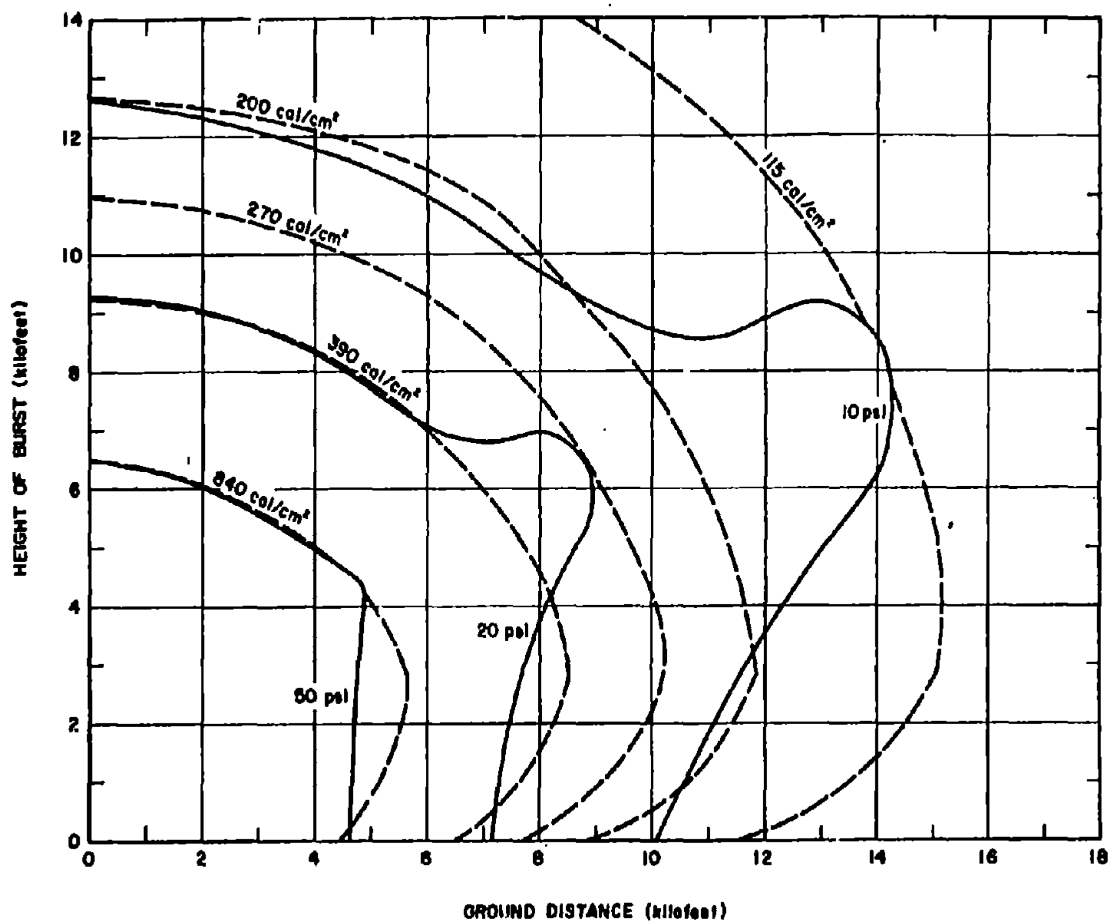

Figure 3-51. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, a Function of Height of Burst and Ground Distance, for 1 megaton, 16 Mile Visual Range, High Overpressure Region [redacted]

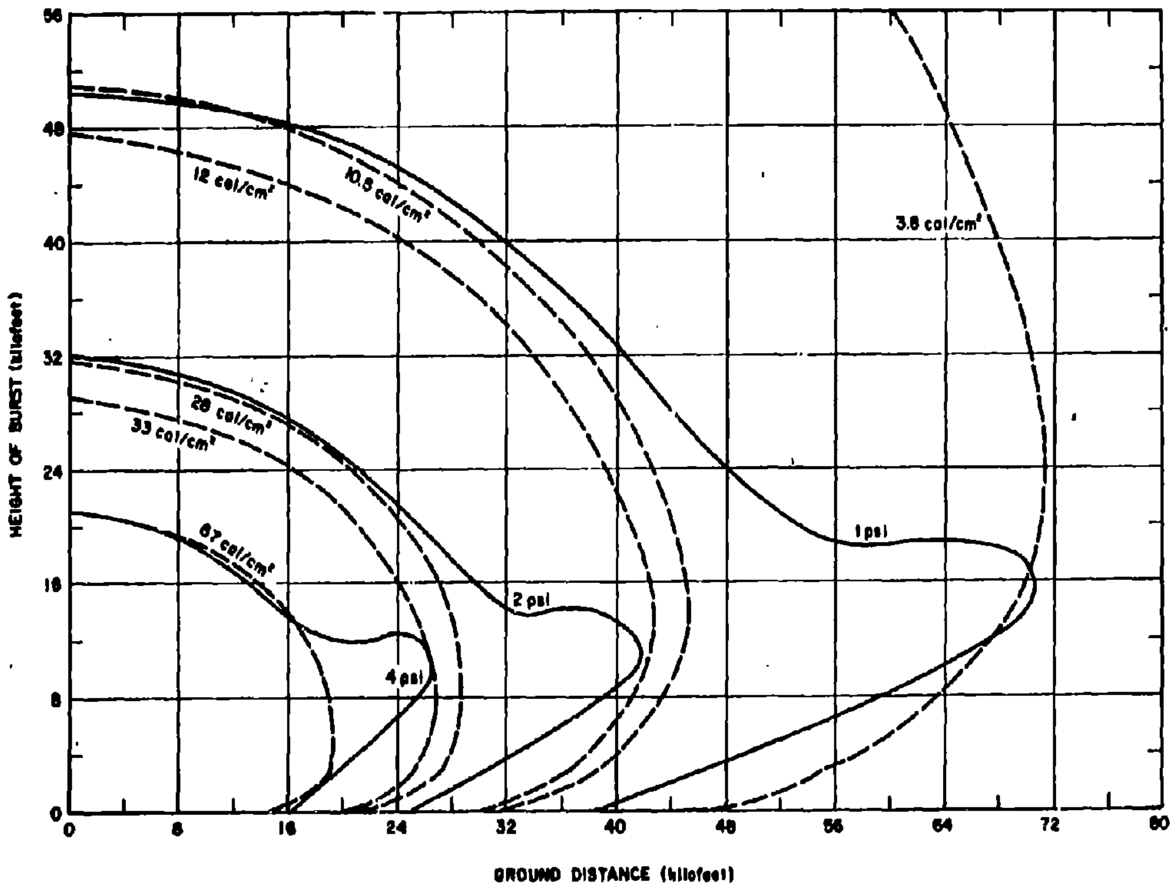

Figure 3-62. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 1 megaton, 16 Mile Visual Range, Low Overpressure Region [redacted]

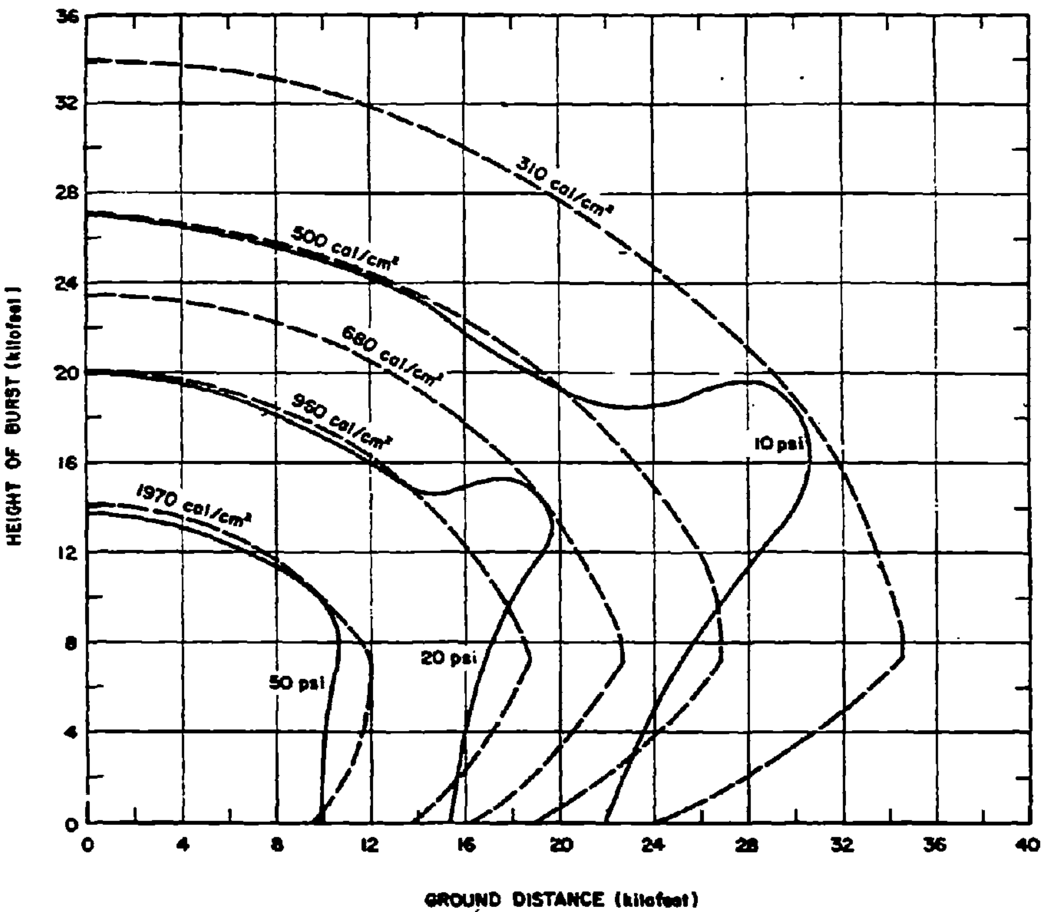

Figure 3-53. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 10 megatons, No Atmospheric Attenuation, High Overpressure Region [redacted]

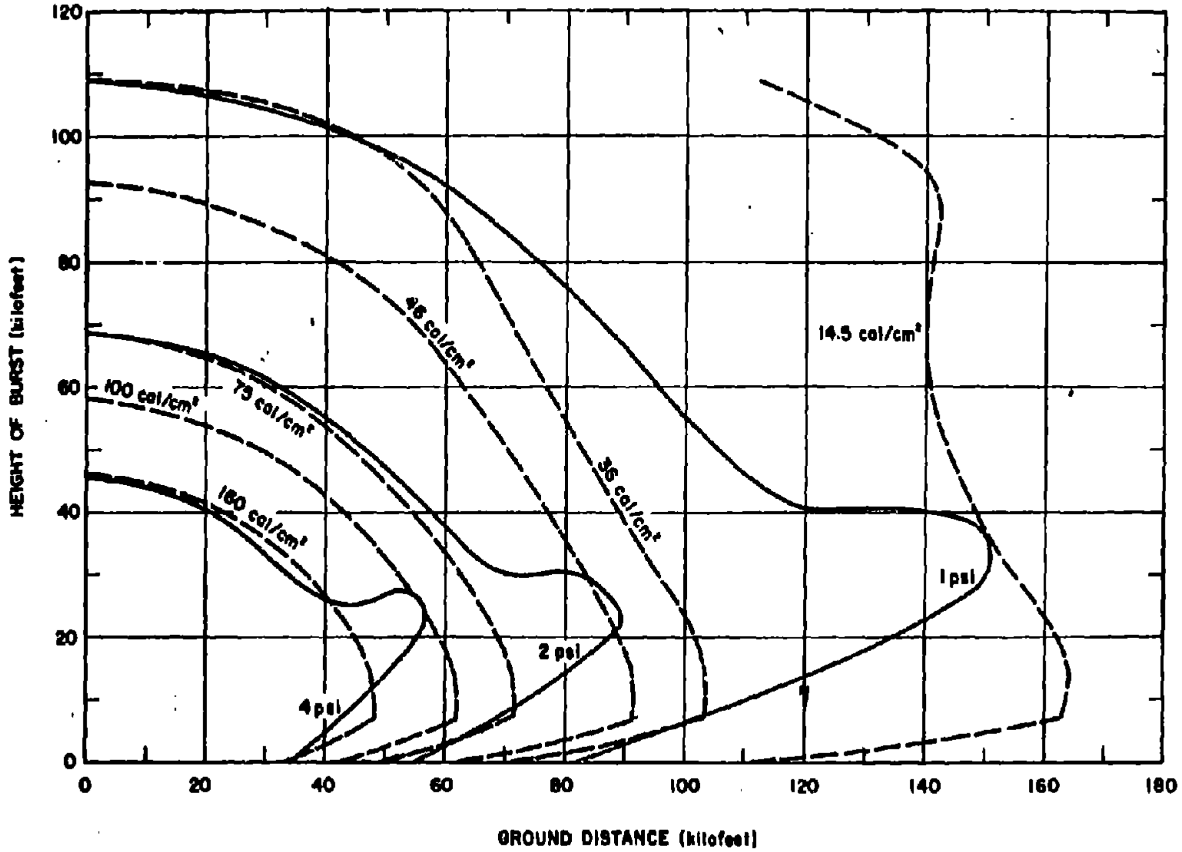

Figure 3-64. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 10 megatons, No Atmospheric Attenuation, Low Overpressure Region [redacted].

[redacted]

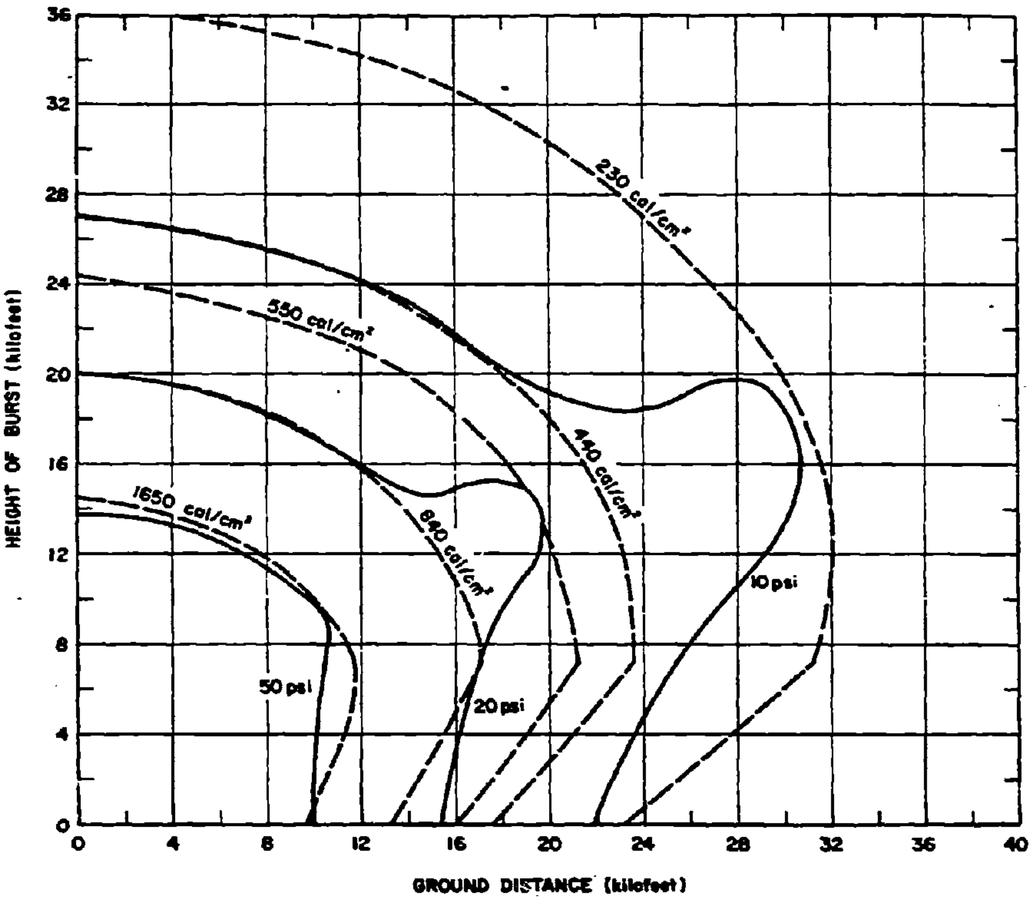

Figure 3-55. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 10 megatons, 16 Mile Visual Range, High Overpressure Region [redacted]

[redacted]

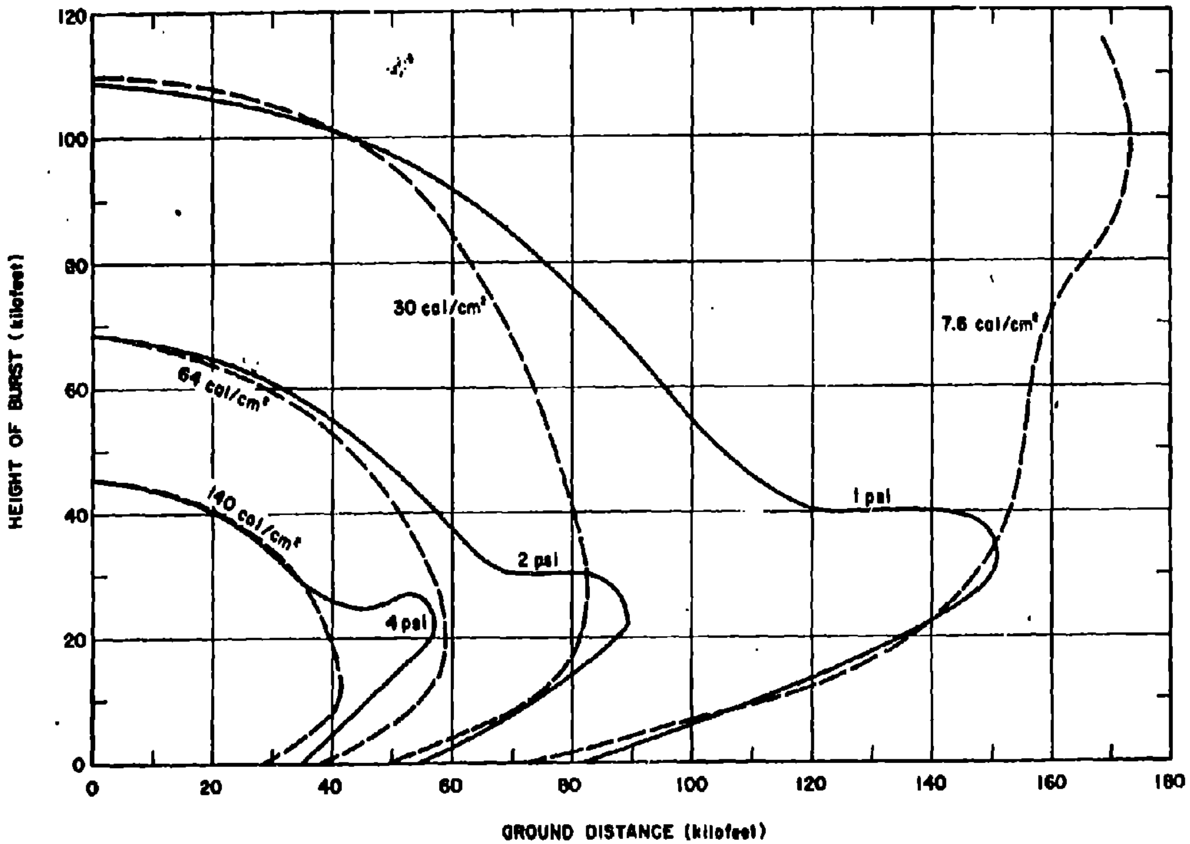

Figure 3-56. [redacted] Free Field Radiant Exposure and Air Blast Overpressure at the Surface, as a Function of Height of Burst and Ground Distance, for 10 megatons, 16 Mile Visual Range, Low Overpressure Region [redacted]

[redacted] PHYSICS OF FIREBALL DEVELOPMENT [redacted]

[redacted] It is not necessary to understand the physics that govern fireball evolution to perform the calculations of the thermal environment that are described in the preceding paragraphs. The following discussion is an introduction to the subject of fireball physics that is intended to introduce certain additional fireball phenomena and to serve as a bridge to more advanced discussions found in the references.

3-22 Black Body Radiation [redacted]

[redacted] A basic principal of physics is that a good radiator is also a good absorber of radiation. Thus, a perfectly black object, i.e., one that absorbs all of the radiation that is incident on it, is an ideal radiator of thermal radiation. Consequently, black body radiation is a convenient standard to which thermal radiation from actual sources can be compared.

[redacted] The radiation properties of nuclear weapons frequently may be described as a black body source of a given temperature or as a combination of several such sources. Paragraph 4-2, Chapter 4, describes the properties of an ideal black body source. Paragraphs 4-4 through 4-7, Chapter 4, describe the spectral characteristics of nuclear weapons in terms of black body sources.

3-23 Opacity [redacted]

[redacted] The flow of energy through a nuclear fireball is strongly affected by the opacity of heated air. The term opacity correctly suggests impedance to the flow of radiation, i.e., energy flows more slowly through those parts of the fireball in which the opacity of the air is high. A less obvious but equally important effect of opacity arises from the physical principle described in paragraph 3-22: in order to be a good radiator of thermal energy a material must also be a good absorber. For this reason the late time fireball cannot radiate effectively. The gas becomes relatively transparent and, as a result, radiates its energy so slowly that it produces negligible thermal damage.

[redacted] In radiation transport theory, the term opacity is assigned a more specific meaning than it has as a nontechnical world. In a medium that absorbs much more radiation than it scatters (this is generally true of the hot gases that constitute the fireball), opacity is the reciprocal of the mean free path, the average distance that a photon travels before it is absorbed. Thus, the units of opacity are reciprocal distance, and values given in the following discussion are in meters^{-1}.

[redacted] The terms "opaque" and "transparent" are used in a less specific sense. A zone of air is opaque if it is thick compared to the mean free path of the radiation passing through it. For example, if a region 1 meter thick has an opacity of 10 meter^{-1} (mean free path = 1/10 meter), it is definitely opaque; if its opacity is 0.01 meter^{-1} (mean free path = 100 meters), it is quite transparent.

[redacted] The opacity of a gas is different for photons of different energy; therefore, the radiation to which the value of opacity applies must be specified. Normally, opacity is given as an average value that represents the transport properties of that black body spectrum which corresponds to the temperature of the gas.

[redacted] There is an optimum value of opacity that allows the fireball to radiate at the highest possible rate. This value is low enough to permit rapid flow of thermal energy from the hot interior of the fireball to the cooler surface layers, but it is high enough that all regions of the fireball are able to radiate the thermal energy that they contain.

[redacted] The physical processes that determine opacity over the range of temperature and photon energies that are of interest are changes in the energy levels of atoms or molecules. At [redacted] photon energies of a few eV* or higher, these processes involve absorption of the photon energy by the electrons of the atom or molecule. At the lower photon energies characteristic of infrared photons, the interactions may involve changes in the vibrational states of atoms. All of these interactions involve changes between two allowable energy states of the atom or molecule. In many cases the photon encounters an atom that has no allowable energy level that exceeds its present energy level by exactly the photon energy. In these cases, absorption of the photon is impossible. Photons of visible light propagating through air illustrate this condition. The photon energy is too high to excite the small changes in molecular energy that certain infrared photons can produce, and it is too low to produce the electronic excitation or ionization that certain photons in the ultraviolet region can produce. Consequently, pure air is transparent to these photons, affecting them only by infrequent scattering interactions.

[redacted] The radiating properties of the fireball and the surrounding air are strongly affected by a particular absorption band of the oxygen molecule, the Schumann-Runge band. Although several mechanisms render air opaque to photons with energies of the order of 10 eV, the Schumann-Runge band is particularly important because it is effective at lower values of photon energy than other strong absorption bands. For this reason, it determines the cutoff energy of the spectrum of transmitted photon energies.

[redacted] The Schumann-Runge band normally absorbs only those photons with energies greater than about 6.7 eV. However, when air is heated to temperatures of a few thousand degrees, oxygen molecules are excited to high vibrational energy levels, with reduces the energy gap between the equilibrium molecular states and the Schumann-Runge continuum. This smaller energy gap reduces the energy that a photon must have in order to induce a transition, and air at 4,000°K absorbs photons with energies as low as 3 eV strongly. This is the photon energy that is associated with violet lights. Thus, the hot layer of air surrounding the luminous region of the fireball removes most ultraviolet energy from thermal radiation, causing fireball radiation to contain a much lower fraction of ultraviolet energy than does sunlight.

3-24 The Fireball Before [redacted] Final Maximum [redacted]

[redacted] A discussion of a low altitude fireball close to the final maximum is valuable for two reasons: this stage of development is of practical interest because the bulk of the thermal pulse is emitted during this final pulse; it is of theoretical interest because most of the physical phenomena affecting all stages of fireball development are active at the time of final maximum. Figure 3-57 shows the opacity properties of a particular fireball in terms of four zones.

- *Zone I:* The hot core of the fireball has a relatively uniform temperature. For this reason, it is called the "isothermal sphere." Since this zone is fairly transparent at most stages of fireball development, thermal energy flows rapidly from hotter regions to cooler ones, and large temperature differences cannot form. At the time shown in Figure 3-57, the opacity is about 1 meter.
- *Zone II:* At the edge of the isothermal sphere, opacity rises rapidly because of increasing air density. Air in this zone not only is more opaque to its own radiation (the mean free path drops to about 12 cm); it has much higher opacity to the higher temperature radiation from the isothermal sphere. Zone I is expanding by heating the air in Zone II; as a result, Zone II has a high temperature gradient. The outer edge of

*[redacted] 1 eV = 1.6×10^{-12} erg.

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Figure 3-57. [redacted] Fireball Properties after Breakaway [redacted]

[redacted]

[redacted] Zone II forms the radiating surface of the visible fireball.

- *Zone III:* Between the fireball and the shock front, air is too cool to radiate energy efficiently. The low opacity of this region to its own radiation reflects this property. This region is, however, opaque to portions of the radiation from Zone II. It absorbs the blue and ultraviolet regions of the spectrum. As a result, it intercepts part of the energy radiated by the fireball and changes the spectral distribution of fireball radiation as seen from a distance.
- *Zone IV:* Ambient air is relatively transparent to infrared, visible, and near-ultraviolet radiation, and will transmit that portion of the fireball radiation that is emitted in this spectral region.

3-25 History of Fireball Evolution [redacted]

[redacted] Most of the stages of fireball development are of little interest in connection with thermal damage, but, for some purposes, the entire sequence of observable phenomena provides useful information. The most obvious application is the comparison of computer calculations with experimental data. This comparison is an excellent indication of the degree to which the computer program simulates actual fireball phenomena.

[redacted] It is not the purpose of this discussion to consider phenomena that contribute only minutely to the total thermal output in detail. The user who desires such detail should consult "Theoretical Models for Nuclear Fireballs [redacted]" DASA 1589, or "Thermal Radiation Phenomena," DASA 1917 (see bibliography).

[redacted] Figure 3-58 shows a calculated power-time curve for a 200 kt burst at 5,000 feet (this curve was presented previously in Figure 3-19 and forms the basis for the standard therm pulse in Figure 3-20). The labeled points correspond to the following events:

1. Deposition of the X-ray energy from the nuclear source produces an extremely hot zone of completely ionized air surrounded by a transition region in which the temperature drops to the ambient value. This transition region is produced by the higher energy X-ray photons radiated by the source. It is hot (and therefore

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Figure 3-58. [redacted] Calculated Power-Time Curves for a 200 kiloton Burst at 5,000 feet [redacted]

[redacted]

[redacted] opaque) enough to obscure visible radiation from the central zone. The radiation that is seen is produced by this so-called X-ray veil.

2. The isothermal sphere continually expands as radiation from the hot plasma is absorbed by the cooler, opaque gases at the edge of the sphere. The jump in radiated power at point 2 occurs as this hot sphere breaks through the X-ray veil and the brightness suddenly increases.

3. As the fireball continues to grow by radiative expansion, it engulfs more and more of the partially opaque air surrounding the veil itself.

4. Hydrodynamic motion, delayed by the inertia of the strongly heated air, has developed to the point that a shock front has formed at the surface of the fireball. The abrupt temperature rise created by the shock front produces a sudden brightening of the fireball surface. This event is partially obscured by the shock precursor, a thin zone of air ahead of the shock front that has been heated by radiation from the shock front. It is similar to the X-ray veil formed at earlier times. The peak at 4 is called the shock formation maximum.

5. As the shock front is attenuated by its expansion, both the shock temperature and the shock precursor temperature fall, and radiated power declines. At 5, the shock precursor is becoming transparent; power starts to increase as radiation from the shock front penetrates beyond the edge of the fireball. This point is called the shock precursor minimum.

6. At some altitudes, a peak known as the debris shock maximum occurs as the shock wave produced by bomb debris overtakes and intensifies the main shock wave. In this case, this event happens to coincide with the shock precursor minimum; therefore, it is not evident on the power-time curve.

7. As the shock precursor continues to cool, radiation from the shock front is transmitted increasingly well, and the traditional first maximum occurs. Power then falls as the shock front drops in temperature. Point 7 is more descriptively termed the shock exposure maximum.

8. The air heated by the shock front, screening the hot regions deeper in the fireball, produces essentially the same phenomenon that was produced at point 5 by the shock precursor. As the air behind the front cools and starts to become transparent, the radiated power first drops and then levels off at the principal minimum as radiation from the hotter inner regions of the fireball begins to penetrate to the outside.

9. During the final maximum (traditionally, the second maximum), the fireball radiates the bulk of the thermal energy. The air behind the shock front continues to become more transparent, and the radiated power comes from the large volume of hot air that constitutes the fireball. As each zone of air radiates its energy and cools below about 6,000°K, it becomes transparent and transmits radiation from a zone closer to the center. Power output drops as the so-called radiative cooling wave propagates inward and the area of the radiating surface decreases.

10. The fireball becomes largely transparent, but is still capable of radiating energy as spectral lines. This final phase of fireball evolution is called the late time radiative phase.

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[redacted] Figure 3-59 shows the way in which the relative timing of some of these events changes with altitude for a 200 kt burst. The numbers in circles are the same numbers that appear in Figure 3-58 to label various events.

[redacted] From the point of view of thermal damage, the most important change that Figure 3-59 shows is that the principal minimum weakens and finally disappears as it merges with the debris-air shock catch-up and the final maximum at high altitudes. This effect changes the shape of the main thermal pulse and is the reason that the standard thermal pulse is roughly representative of thermal pulses only at altitudes below about 100,000 feet.

3-26 Comparison with Recent Analysis of Experiments [redacted]

[redacted] Although, as mentioned previously, the computer calculations agreed well with the experimental data with which they were compared, and the calculations form the basis for a complete set of data that is compatible and can be put into a form that is suitable for this manual, they do not necessarily represent the ultimate answers. A set of semi-empirical equations has recently been developed that give t_{max} and t_{min} of the thermal pulses produced by bursts up to 100 kilometers. These equations are

$$t_{max} = 0.042\ (\rho W)^{0.44}\ (\rho_s/\rho)^{-\rho_s/\rho}\ \text{sec},$$

[redacted]

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Figure 3-59. [redacted] Altitude Variation of Phenomena for a 200 kiloton Burst [redacted]

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[redacted] where ρ is the atmospheric density at burst altitude, and ρ_s is the density at the "singular" altitude for the yield being considered, which is the altitude at which the thermal pulse changes from a two peaked pulse to a single peaked pulse, and which is given by

$$\rho_s = 0.033\ W^{-1/2},$$

and

$$t_{min} = 0.00365\ (\rho W)^{0.44}\ \text{sec.}$$

For comparative purposes, these values are plotted together with the equations given previously for t_{max} and t_{min} as a function of yield for scaled burst heights of 180 $W^{0.4}$ feet, i.e., low air bursts, in Figure 3-60. This one comparison is presented only to show some of the uncertainty associated with the prediction of the thermal radiation environment. As pointed out previously, the computer calculations were used as the basis for the prediction of the thermal environment in this manual for several reasons, one being that they provide a complete description of all of the various phenomena in a compatible format. Further investigations may reveal that changes in the presentation of the data are required.

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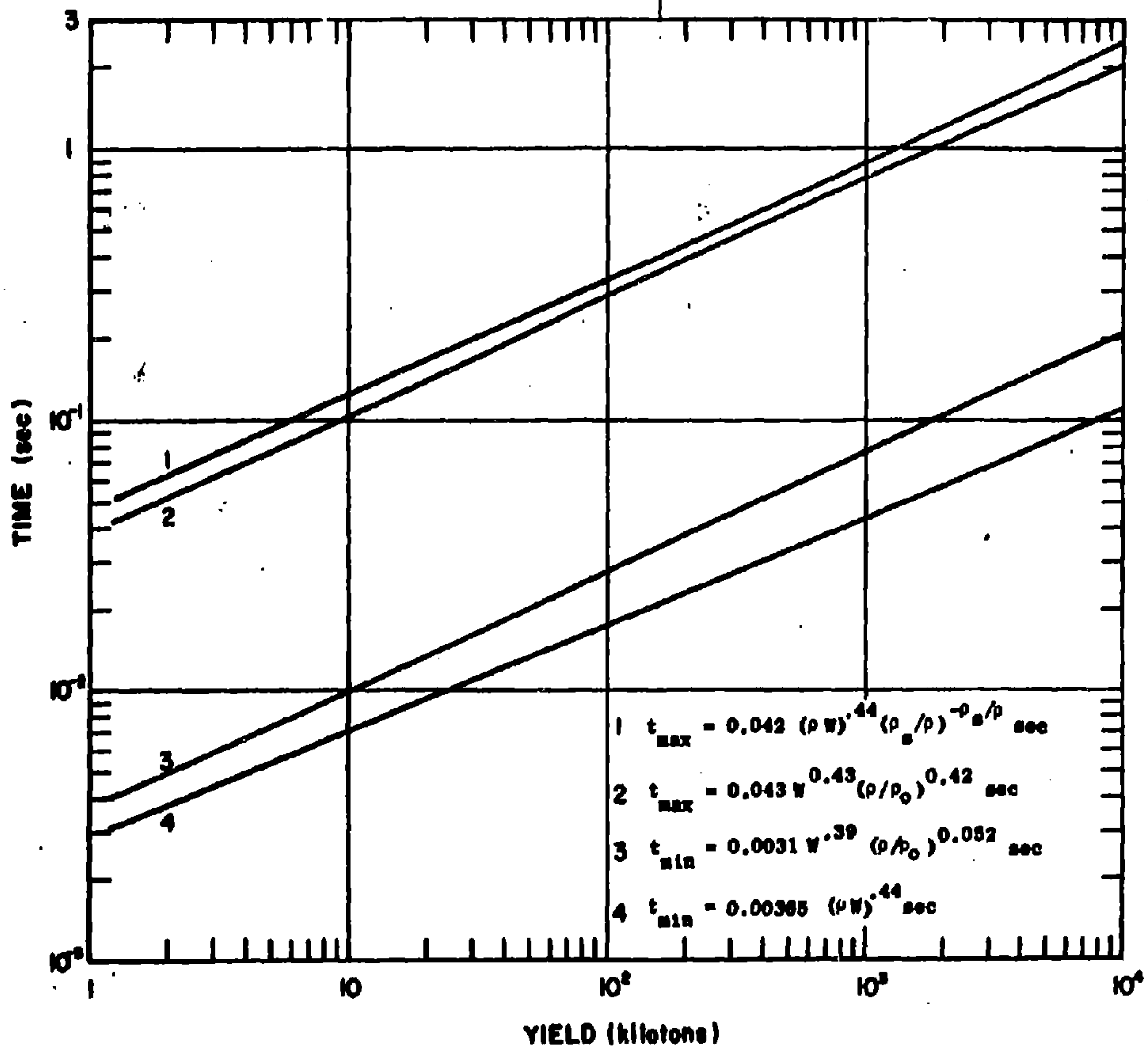

Figure 3-60. [redacted] Comparison of Equations for t_{min} and t_{max}, $HOB = 180\ W^{0.4}$ feet [redacted]

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